CONTRACTORS REPORT NO. 995
NASA CR-165470

LIGHTWEIGHT DIESEL ENGINE DESIGNS FOR COMMUTER TYPE AIRCRAFT

(NASA-CR-165470) LIGHTWEIGHT DIESEL ENGINE DESIGNS FOR COMMUTER TYPE AIRCRAFT (Teledyne Continental Motors, Muskegon, Mich.) 70 p HC A04/MF A01 CSCL 21E

N82-11068

Unclas
G3/07 08165

Alex P. Brouwers
Teledyne Continental Motors
General Products Division
76 Getty Street
Muskegon, Michigan 49442

JULY 1981

PREPARED FOR:

NASA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135
CONTRACT NAS3-22149

CONTRACTORS REPORT NO. 995
NASA CR-165470

LIGHTWEIGHT DIESEL ENGINE DESIGNS FOR COMMUTER TYPE AIRCRAFT

Alex P. Brouwers
Teledyne Continental Motors
General Products Division
76 Getty Street
Muskegon, Michigan 49442

JULY 1981

PREPARED FOR:
NASA
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
21000 BROOKPARK ROAD
CLEVELAND, OHIO 44135
CONTRACT NAS3-22149

TELEDYNE CONTINENTAL MOTORS
General Products Division

4244/7-81

TABLE OF CONTENTS

1.0 SUMMARY

This report describes the conceptual design and performance of two lightweight diesel engines for commuter type aircraft, capable of developing 1491 kW (2000 SHP) and 895 kW (1200 SHP) nominal propeller power at takeoff. The engines are flat rated to 4572 m (15000 ft.) altitude. The configurations and technologies that are applied are aimed at obtaining the best practical fuel consumption and the lightest power plant within the 1990's time frame specified. They are:

1. A radial cylinder configuration
2. Two-stroke cycle operation.
3. Insulated cylinders
4. Turbocompounding
5. High-pressure injection system
6. Advanced material technologies

The specific fuel consumption of the 1491 kW (2000 SHP) engine is projected at 182 g/kWh (.299 lb./HPh) at 4572 m (15000 ft.) cruise altitude. The weight of the engine is projected at 620 kg (1365 lb.) when advanced materials are applied resulting in a specific weight of .415 kg/kW (.683 lb./HP).

The specific fuel consumption of the 895 kW (1200 HP) engine is projected at 187 g/kWh (.308 lb./HPh) at 4572 m (15000 ft.) cruise altitude. The weight of this engine is projected at 465 kg (1025 lb.) when advanced materials are applied or .520 kg/kW (.854 lb/HP).

The study includes scaling information on the physical characteristics and engine performance over a power range from 670 kW (900 SHP) to 1865 kW (2500 SHP).

An advanced technology diesel engine with its very low SFC and light weight appears to be an attractive candidate for aircraft applications.

2.0 INTRODUCTION

2.1 Purpose of the Study

High propulsion system performance and fuel economy is essential for better airplane capabilities and enhanced usefulness of new airplane applications. Current commuter aircraft engines operate at reasonable levels of efficiency and reliability. However, the cost of fuel is becoming an increasingly larger factor in the operation of commercial aircraft.

The purpose of this study is to define conceptual designs and performance of advanced technology lightweight diesel engines which could be fuel-efficient alternative power plants to be used in studies of future commuter type aircraft.

Previous NASA funded studies of lightweight diesel engines for general aviation aircraft have shown that the diesel is a very fuel-efficient attractive alternate engine candidate. The diesel engine historically offers outstanding fuel economy and an ability to operate on a wide range of fuels. Advanced design and material technologies have the potential to substantially reduce weight and bulk and make the diesel engine a competitive power plant for commuter type aircraft.

2.2 Previous Large Aircraft Diesel Engines

Although there have been many different aircraft diesel engines built, only two large engines were relatively successful and are listed because of their historical significance. Any new diesel engine proposed in this study with advanced technology would certainly have to show performance potential beyond these engines which are presented in Table I.

2.3 Scope of the Study

The scope of the study is to perform a conceptual design, including performance and scaling investigation of two advanced technology aircraft engines of 1491 kW (2000 SHP) and 895 kW (1200 SHP) takeoff power for the 1990 time period. The study defines the configurations, technologies and physical characteristics of the engines and their performance in all flight regimes up to 7620m (25000 ft.) altitude. The engine performance requirement was a flat rating horsepower capability from sea level takeoff to 4572 m (15000 ft.)

2.4 Relative Merit of this Study to the General Field

Although the study relates to commuter aircraft, the technologies described are as well applicable to other fields such as long range transports, helicopters, military vehicles and marine vessels where weight of the power plant and low fuel consumption are of extreme importance.

2.5 Significance of the Project

The study has shown that the diesel engines have the potential for very low weights and significantly reduced fuel consumption when compared to current engines. Advanced technologies, such as adiabatic operation, turbocompounding and lightweight materials are used in this study.

TABLE I
Previous Aircraft Diesels

		Junkers 207 Turbo	Napier Nomad
No. of Cylinders		6	12
Crankshaft	kW	746	1984*
T.O. Power	HP	1000	2660
Compounded	kW		2274**
T.O. Power	HP		3050
Cooling		Liquid	Liquid
Cycle		2-Stroke	2-Stroke
Bore	mm	120	152.4
	in	4.724	6.000
Stroke	mm	2 x 160	187.3
	in	2 x 6.299	7.375
Displ.	1	21.7	41.0
	in^3	1325	2502
RPM		3000	2050
BMEP	bar	6.88	14.16
	psi	100	205
Piston Speed	m/s	16.0	12.8
	fpm	3150	2520
Spec. Power	kW/1	34.4	48.4 *
	HP/in^3	.75	1.06
Weight	kg	649	1624
	lb	1430	3580
Spec. Weight	kg/kW	.87	.71**
	lb/HP	1.43	1.17
BSFC	g/kWh	219	210**
	lb/HPh	.360	.345

*Piston Engine Power Only
**Compounded

3.0 DESIGN STUDY OF THE 1491 kW (2000 SHP) ENGINE

An initial preliminary study was conducted to determine the effect of current technologies and configuration on a diesel power plant.

3.1 Prelimary Configuration Analysis Utilizing Modification of Past Aircraft Diesel Engine Data

This analysis assumes that any power plant resulting from this study will be designed with improvements over the last generation aircraft diesel engines by utilizing current diesel technologies.

To obtain an initial approximation of the amount of improvement that may be possible by applying new technologies, the Napier Nomad aircraft diesel engine was used as a baseline upon which hypothesized new technologies were added. Although the ultimate configuration of the engine resulting from this study turned out to be quite different, the credibility of the analysis is supported by this initial hypothetical modified Nomad.

The simulation assumes that the cylinder cooling can be reduced by 30% based on today's advanced air-cooled engines.

The performance data of the original Nomad engine are:

Piston engine power	1983 kW (2660 HP)
Excess turbine power	291 kW (390 HP)
SFC	210 g/kWh (.345 lb/HPh)
Fuel flow	478 kg/h (1052 lb/h)

Cooling test data of modern fully air-cooled diesel engines shows that cylinder cooling losses are approximately 13% of the energy input. Assuming a 30% reduction of these losses and 55% of the additional heat in the exhaust is recovered in the turbine, it follows that an additional 122kW (163 HP) turbine power would be available for turbocompounding by this reduction in cylinder cooling.

The performance data of this hypothetical Nomad engine then would have been:

Piston engine power	1983 kW (2660 HP)
Excess turbine power	413 kW (554 HP)
SFC	200 g/kWh (.328 lb/HPh)
Fuel flow	478 kg/h (1052 lb/h)

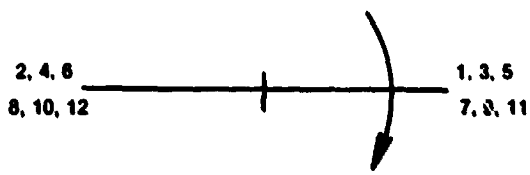
The piston engine portion of the overall turbocompound engine thus would contribute 83% of the total power.

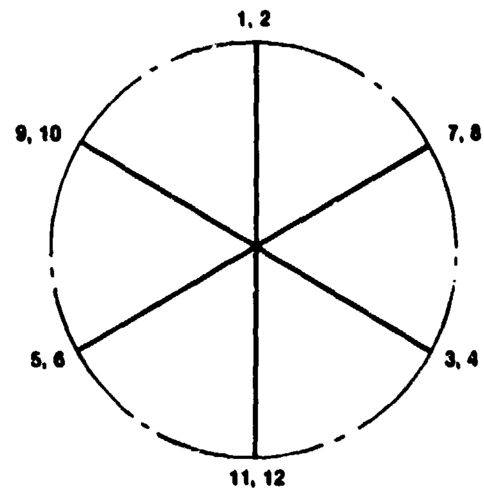
Based on this value, initial approximations of the piston engine size could now be projected for a new engine at this hypothetical technology level, i.e. reduced cooling.

Disadvantages are:

- Requires a tunnel-crankcase
- Requires a barrel crankshaft (cheeks and made journal in one large disc). This type of shaft is heavy and can not be 100% balanced.

2. Opposed cylinders.





Firing order:

1, 12 — 9, 4 — 5, 8 — 11, 2 — 3, 10 — 7, 6 — 1, 12

Advantages are:

- Simple, vertically-split crankcase.
- Turbomachinery and accessories can be mounted above and below crankcase, thus offsetting the disadvantage of the longer crankcase on overall engine length.
- The crankshaft is easy to balance.
- There is no problem providing pendulum dampers.

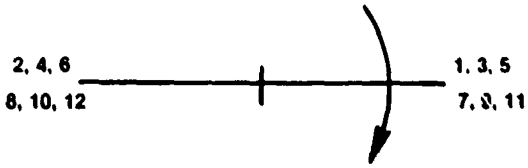
Disadvantages are:

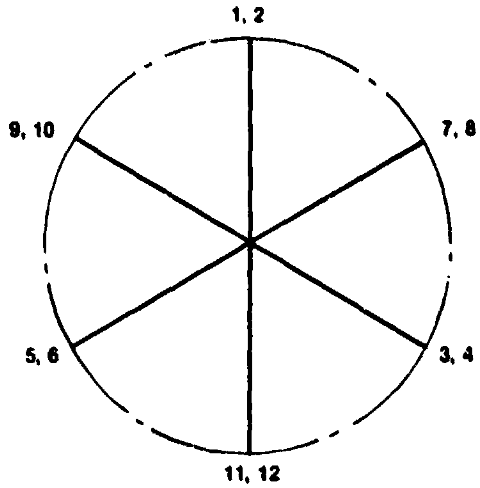
- Increased engine weight due to longer crankcase and crankshaft.
- Two cylinders fire simultaneously, but always on opposite banks.
- Air-cooling will require more attention in the design phase than in the case of the radial engine.

Disadvantages are:

- Requires a tunnel-crankcase
- Requires a barrel crankshaft (cheeks and made journal in one large disc). This type of shaft is heavy and can not be 100% balanced.

2. Opposed cylinders.





Firing order:

1, 12 — 9, 4 — 5, 8 — 11, 2 — 3, 10 — 7, 6 — 1, 12

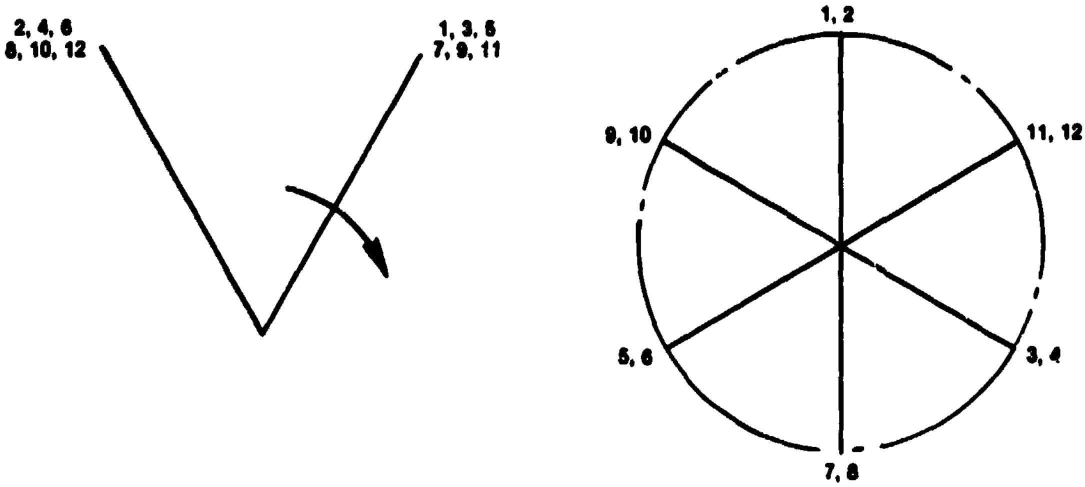
Advantages are:

- Simple, vertically-split crankcase.
- Turbomachinery and accessories can be mounted above and below crankcase, thus offsetting the disadvantage of the longer crankcase on overall engine length.
- The crankshaft is easy to balance.
- There is no problem providing pendulum dampers.

Disadvantages are:

- Increased engine weight due to longer crankcase and crankshaft.
- Two cylinders fire simultaneously, but always on opposite banks.
- Air-cooling will require more attention in the design phase than in the case of the radial engine.

3. 60° V



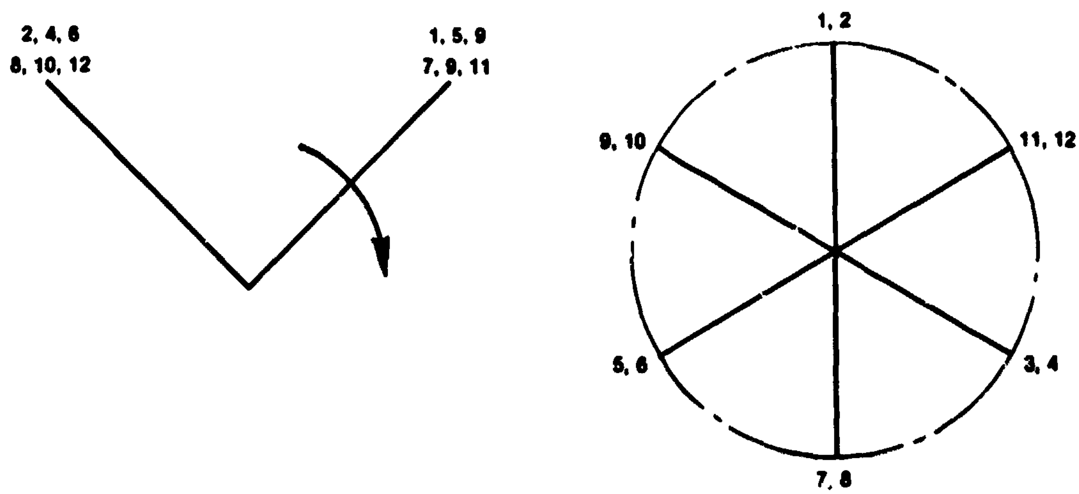
Firing order:

1, 10 — 9, 6 — 5, 8 — 7, 4 — 3, 12 — 11, 2 — 1, 10

Disadvantages are:

- Two cylinders fire simultaneously.
- Side loads on main bearing caps require a heavy crankcase structure.
- There is not much room inside the V for accessories.

4. 90° V



Firing order:

1 — 6 — 9 — 8 — 5 — 4 — 7 — 12 — 3 — 2 — 11 — 10 — 1

Advantages are:

- Regular 30° firing intervals.
- There is more room inside the V for accessories.

Disadvantage:

- Side loads on main bearing caps.

As a result of this initial evaluation opposed cylinders appear to be the best solution for a multi-cylinder configuration.

3.1.3 EVALUATION OF TECHNOLOGIES

Based on the results of 3.1.2 a 12 cylinder engine with opposed cylinders was initially assumed and other relevant parameters were further evaluated. These included:

1. Cooling

A. Air-cooling

The advantages of air-cooling are:

- The cylinders can be individual: easy for maintenance and replacement.
- Air-cooling is more reliable:
  - No moving parts
  - No leaks

The disadvantages of air-cooling are:

- The cooling fins result in a larger cylinder spacing and thus a longer crankcase.
- More care needs to be taken to get adequate cooling of all cylinders.

B. Liquid-cooling

The advantages are:

- Equal cooling conditions of all cylinders.
- Shorter crankcase.

The disadvantages are:

- Less reliability.
- The bulk of a radiator is added to the engine.

C. Effect of type of cooling on overall engine weight:

A previous study of the 300 and 150 kW engines — NASA Report CR3260, — shows little difference in engine weights:

Air-cooled	1.277 kg/kW
Liquid-cooled	1.242 kg/kW

A comparison is offered by two McCulloch aircraft engines:

TSIR-5190 Water-cooled, gasoline — excluding radiator and water pump
201 kW, 179 kg (270 HP, 394 lb)
Spec. weight .89 kg/kW (1.46 lb/HP)

TRAD-4180 Air-cooled, diesel
150 kW, 149 kg (201 HP, 329 lb)
Spec. weight .99 kg/kW (1.63 lb/HP)

The higher specific weight of the diesel engine is due to higher firing pressures.

D. Decision criteria

The liquid cooled engine has the disadvantage of requiring a radiator and a water pump. This adds to the size of the power plant, reduces the reliability and requires more maintenance.

	Air-cooled	Liquid-cooled
Reliability	+	
Bulk	+	
Weight	Same	Same
Fuel economy	Same	Same
Technology	Same	Same
Maintainability	+	
Integration	+	
Drag	Same	Same

Recommendation: Air-cooled design

2. Cycle selection

The **two-stroke cycle** system is selected for the same reasons outlined in the NASA reports CR3260 and CR3261.

Advantages:

- One power stroke per revolution.
- It results in a reduction of the engine weight due to the elimination of the valve trains, camshafts and camshaft drive.
- Engine reliability is improved.
- Engine frontal area is reduced, due to the elimination of the valves resulting in less frontal drag.

Disadvantage:

Severe conditions are imposed on the turbocharger:

- Compressor air flow is high because scavenge air must be delivered in addition to the combustion air.

- The turbine inlet temperature is reduced due to the mixing of the exhaust gas and the scavenge air.

This analysis of a turbocompounded, opposed 12 cylinder, air-cooled 2-stroke cycle configuration indicates that such an engine will be large and heavy. The predicted compounded BSFC of 200 g/kWh (.328 lb./HPh) is good but much higher than can be expected for a compounded power plant with insulated cylinders. (BSFC's less than 182 g/kWh — .300 lb./HPh — have been obtained with the CUMMINS adiabatic engine.) It was, therefore, concluded that an engine which utilizes state-of-the-art technologies will not be competitive with current commuter power plants. As a result of this initial analysis the modified Nomad configuration was discarded.

Advanced technogies must be applied:

1. High BMEP's

2. High piston speeds

3. Insulated cylinders (reduced cooling)

4. High-pressure fuel injection.

5. Lightweight materials and components

6. High performance turbine and compressor.

3.2 Configuration and Technology Analysis of an Advanced 1491 kW (2000 SHP) Engine

An all new engine concept based on technology developed in other NASA studies (Ref. 1 and 2) was assumed. After several iterations and trade-offs the resultant configuration schematic is shown in Figure 3-1.

3.2.1 ENGINE FEATURES

The configuration and technologies applied to the commuter type engine to obtain practical low fuel consumption and light weight are:

1. A radial cylinder configuration.

   Prior NASA funded studies of diesel engines for general aviation aircraft (NASA reports CR3260 and CR3261) have shown that this configuration results in the lightest possible power plant for a given engine power. These studies also showed that the radial configuration does not result in an excessively large frontal area of the engine.

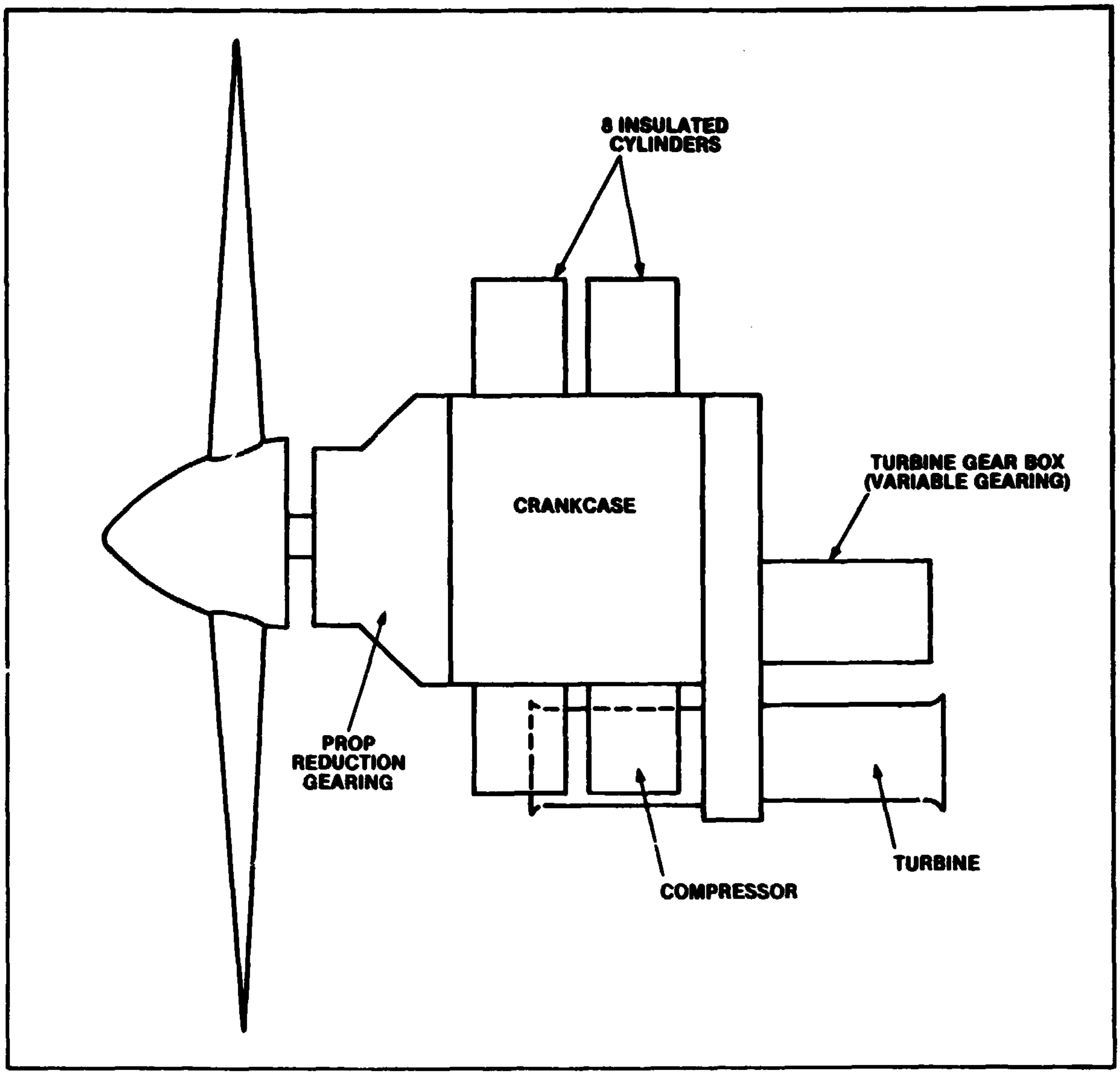


FIGURE 3-1 — SCHEMATIC OF THE 1491 kW 2-STROKE CYCLE ENGINE

2. Insulated cylinders.

   As discussed in paragraph 3.1 significant gains are available by using insulated cylinders. With insulated cylinders the diverted cooling energy results in an increase of the enthalpy of the exhaust gases and is partially recovered in the turbine.

3. Turbocompounding.

   The excess power from the turbine is fed back into the propeller gear train. More useful power can thus be obtained from the same amount of fuel. This results in very low SFC's of the power plant.

4. High-pressure injection system.

One of the most critical technologies of the proposed engines is the fuel system. The primary prerequisite for optimum combustion efficiency is a thorough mixing of fuel and air. In a four-stroke cycle engine this is in part accomplished by the swirling motion of the air in the cylinder. Optimum scavenging of the cylinder of a loop-scavenged two-stroke cycle engine, however, dictates the absence of induced turbulence. The mixing of fuel and air must thus be obtained by maximum penetration and atomization of the fuel. This requires high injection pressures.

Additionally, the thorough mixing of air and fuel combined with the high temperatures of insulated cylinders, make the engines less sensitive to the type and quality of the fuel.

5. Advanced material technologies.

The use of composites and high-strength materials will result in appreciable weight reductions.

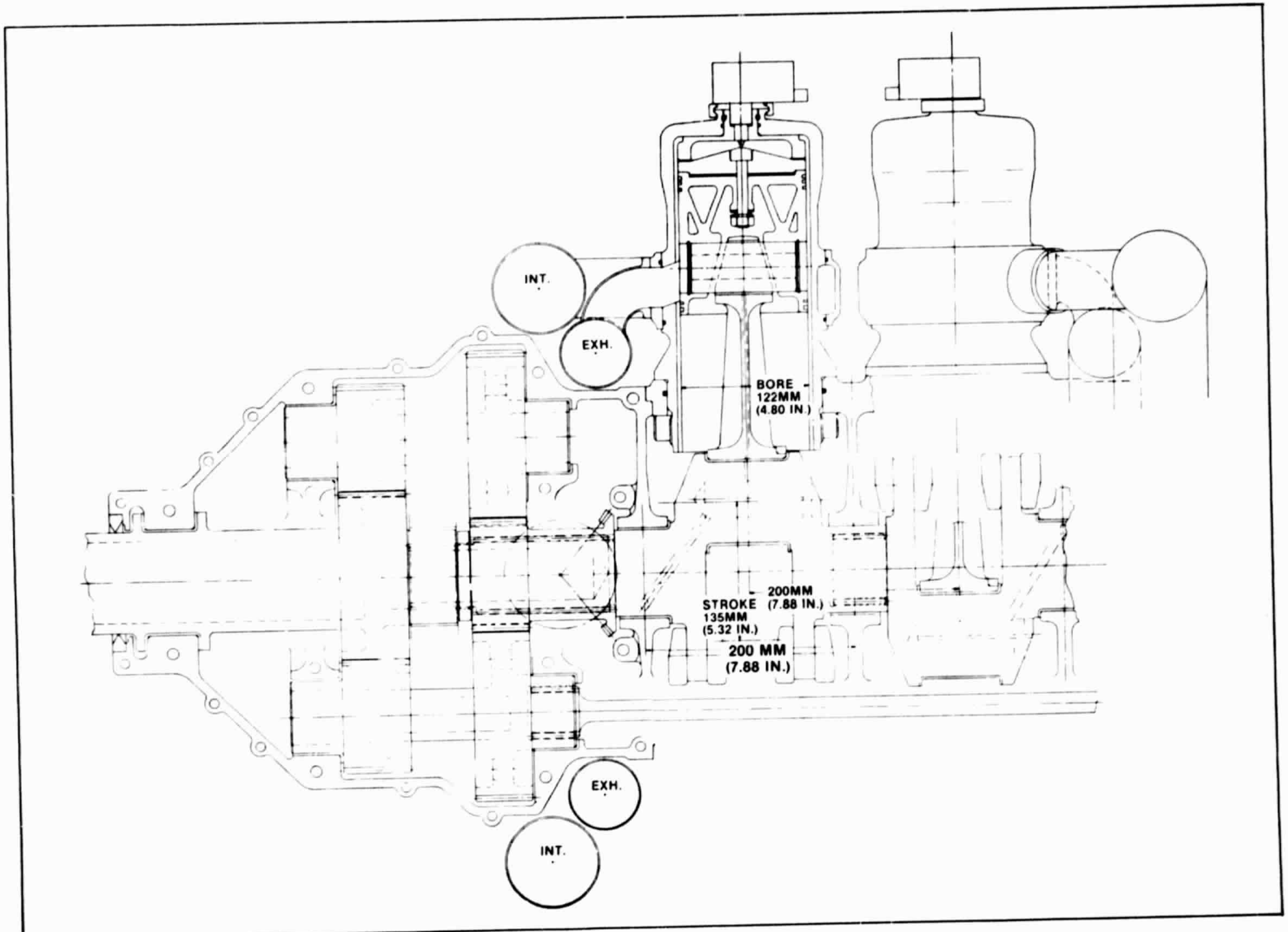


FIGURE 3-2 — 1491 kW COMMUTER AIRCRAFT DIESEL PARTIAL LONGITUDINAL SECTION

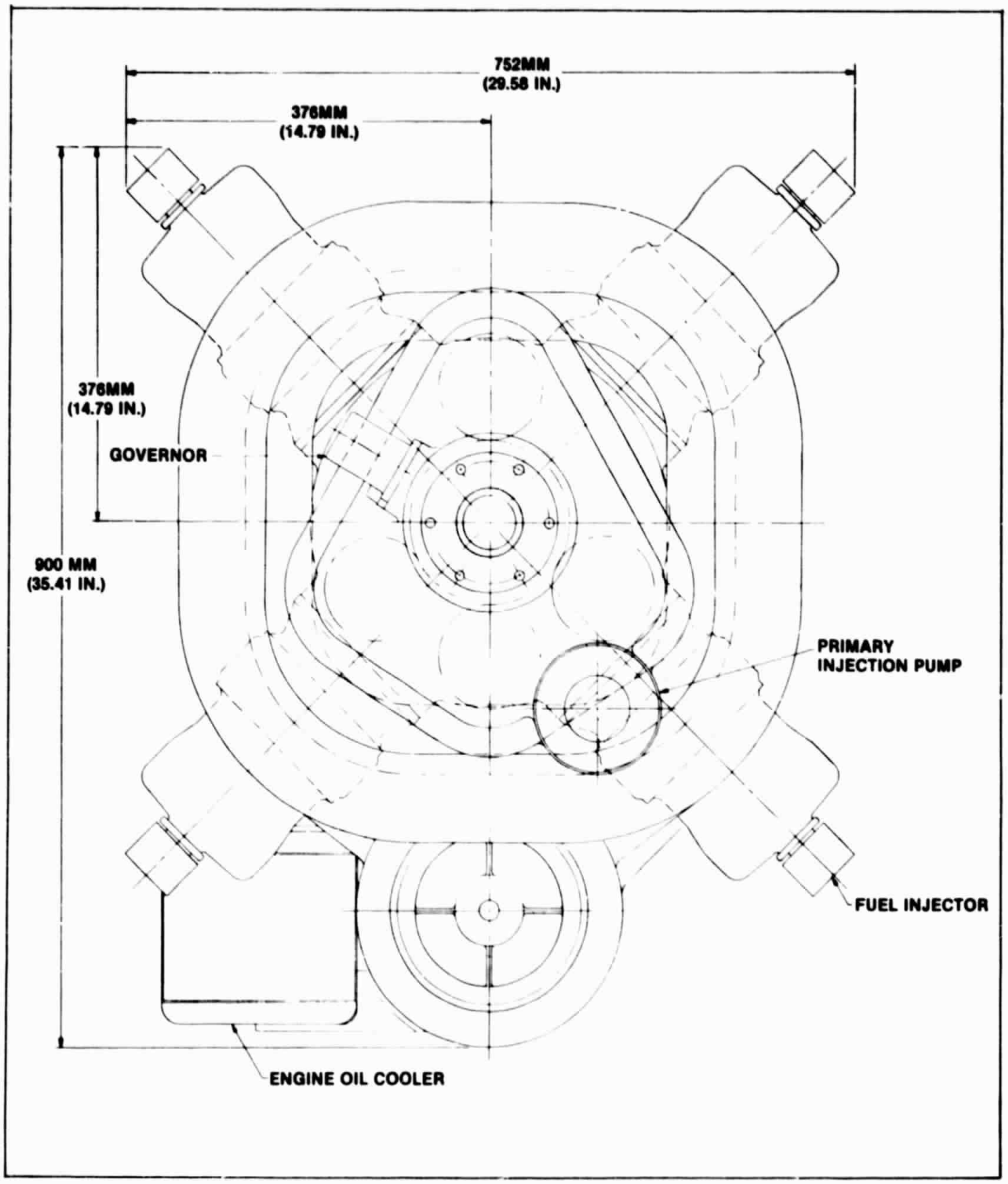


FIGURE 3-3 — 1491 kW COMMUTER AIRCRAFT DIESEL — FRONT VIEW

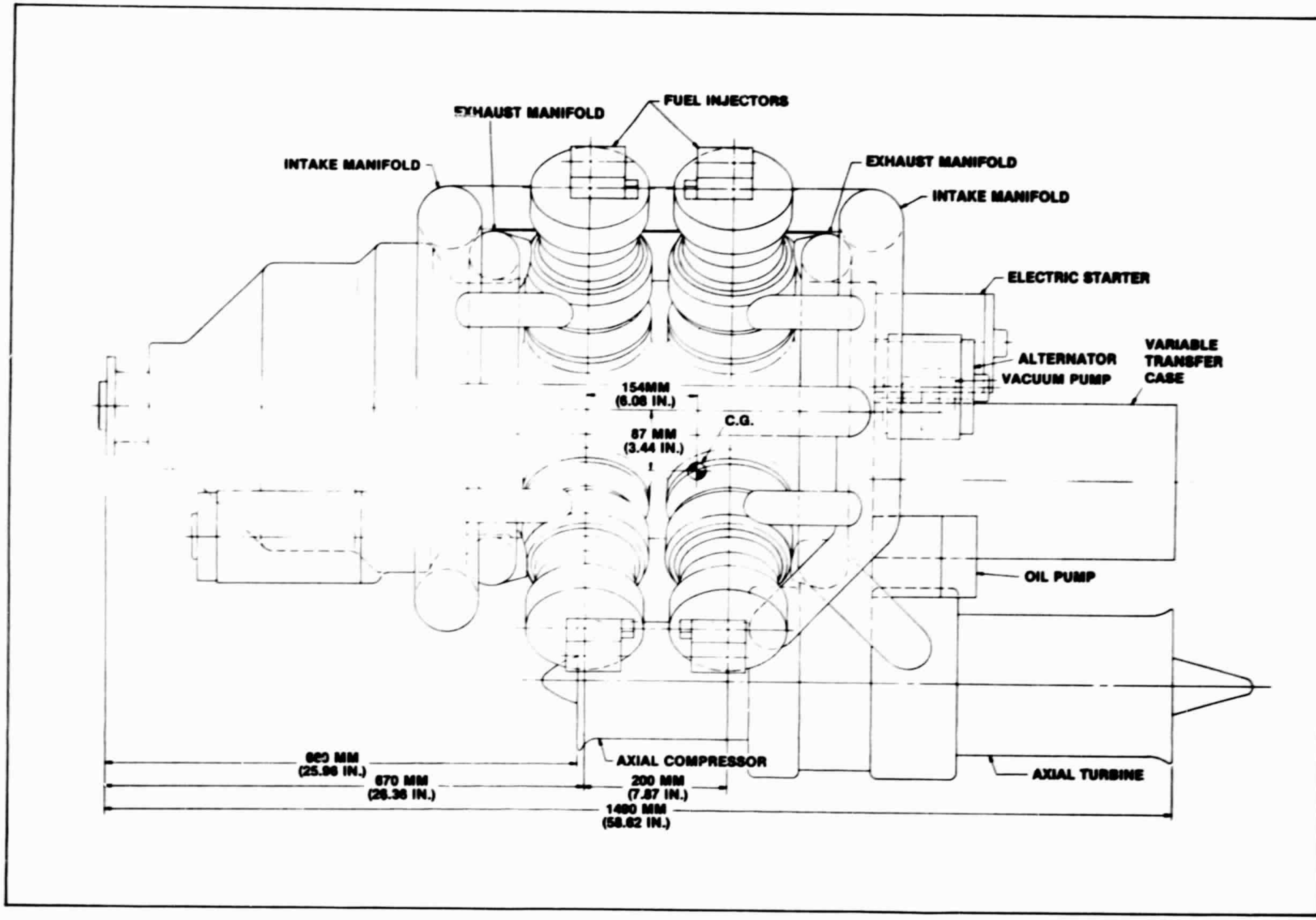


FIGURE 3-4 — 1491 kW COMMUTER AIRCRAFT DIESEL — SIDE VIEW

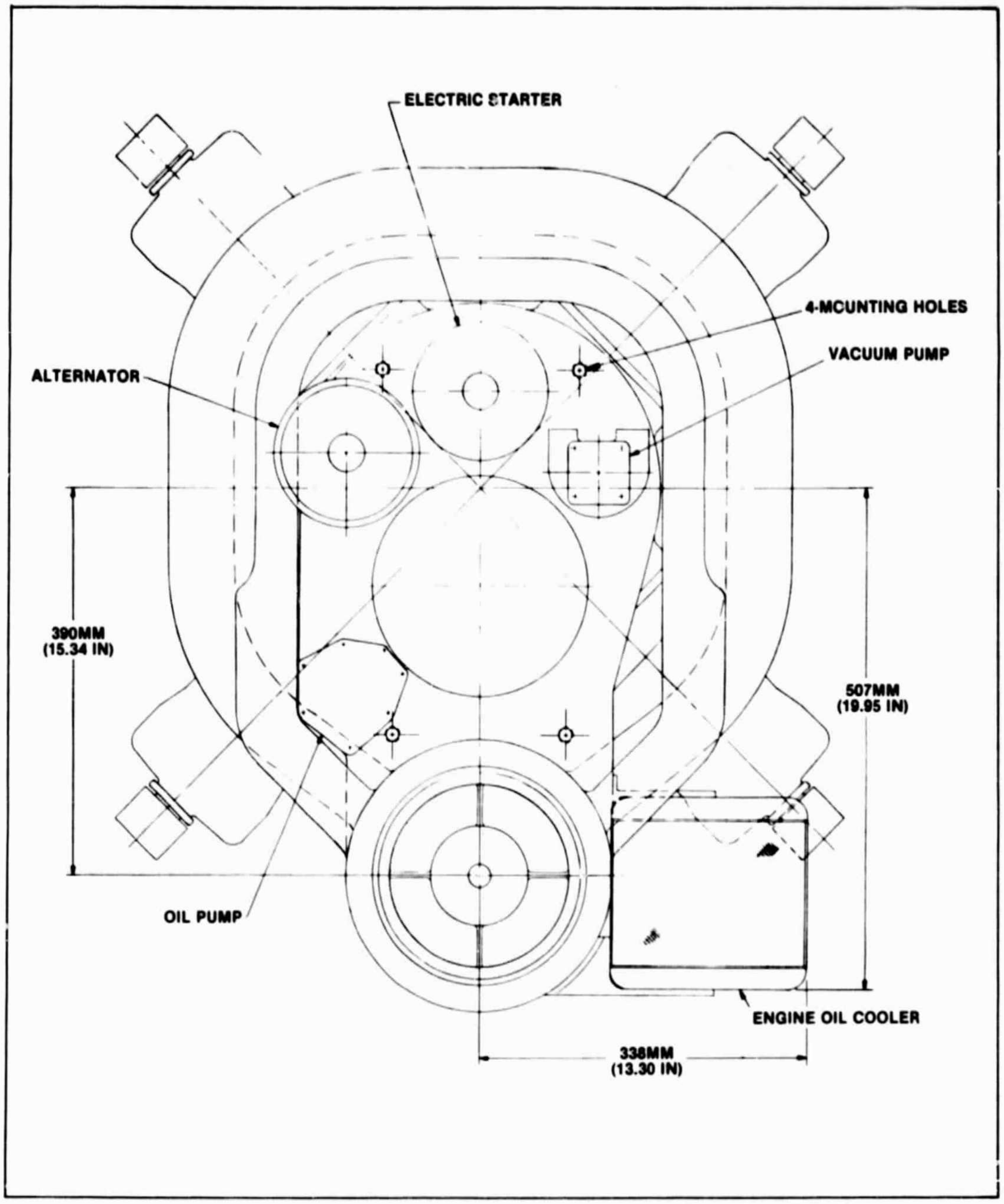


FIGURE 3-5 — 1491 kW COMMUTER AIRCRAFT DIESEL — REAR VIEW

3.2.2 ENGINE CONCEPT DESIGN

Three views and a partial section of the engine are shown in the Figures 3-2 through 3-5.

The eight cylinder arrangement which was finally chosen is a compromise between frontal area and weight of the engine.

The experience gained in the design of the general aviation diesel engines (NASA report CR3261, page 9) indicates that the lightest possible radial engine is obtained when the lowest number of cylinders is chosen for a given engine displacement.

The cylinders are arranged in two rows of four cylinders each. Locating the cylinders at a 45° angle allows placement of the compressor between the bottom cylinders. The Schnuerle type loop scavenging system is chosen because it is known to require the least amount of scavenge air, which in turn reduces the required compressor power, Figure 3-6.

The cylinder liners and the tops of the pistons utilize insulating materials in order to retain as much heat in the exhaust gases as possible.

The propeller reduction gearing consists of driving and driven sun gears and three sets of compound pinions.

No manifolds are located between the two rows of cylinders in order to keep the crankcase as short and stiff as possible.

The compressor and the turbine are both of the axial type. The axial staging is chosen for the following reasons:

1. Axial units have less bulk and weigh less than radial ones, in particular for high mass flows.

2. The high compressor pressure ratio (8:1) required for cruising can be obtained more easily with an axial unit than with a centrifugal compressor.

3. The overall diameter of the compressor housing is small and allows for a very favorable packaging location between any of the cylinders. The design shown arbitrarily has the turbocompressor located on the bottom of the engine.

The turbine is connected to the crankshaft by means of an infinitely variable speed reducing device. This allows a high compressor speed at starting and low engine speeds and prevents overspeeding at high engine speeds.

Conventional starter and alternator units are located at the rear of the engine. A separate turbocharger-mounted alternator for independent electrical power and air starting was initially considered. This scheme would be similar to that proposed in CR3261 for the 186 kW engine (Figure 3-7). Although this is a desirable feature, it required a complete weight and performance trade-off study between the alternatives which was beyond the scope of this study. When such a trade-off study is made consideration should be given to utilize a separate auxiliary power unit to supply electrical power independent of the main engine. This APU could then also be a source of hot compressed air for preheating of the engine on cold days and provide air for a bleed air starter.

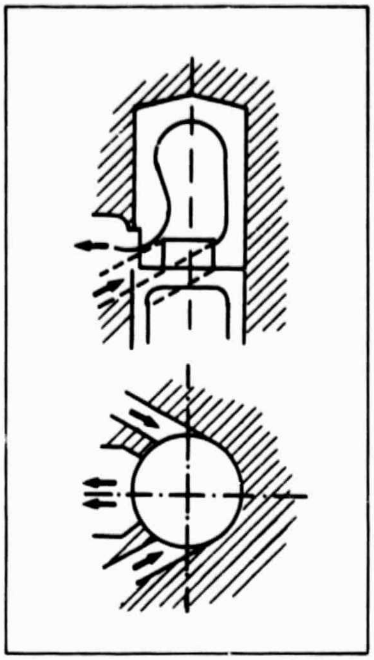


FIGURE 3-6 — SCHNUERLE TYPE LOOP SCAVENGING

3.2.3 ENGINE OPERATING DATA

Engine operating parameters were determined for 5 flight conditions:

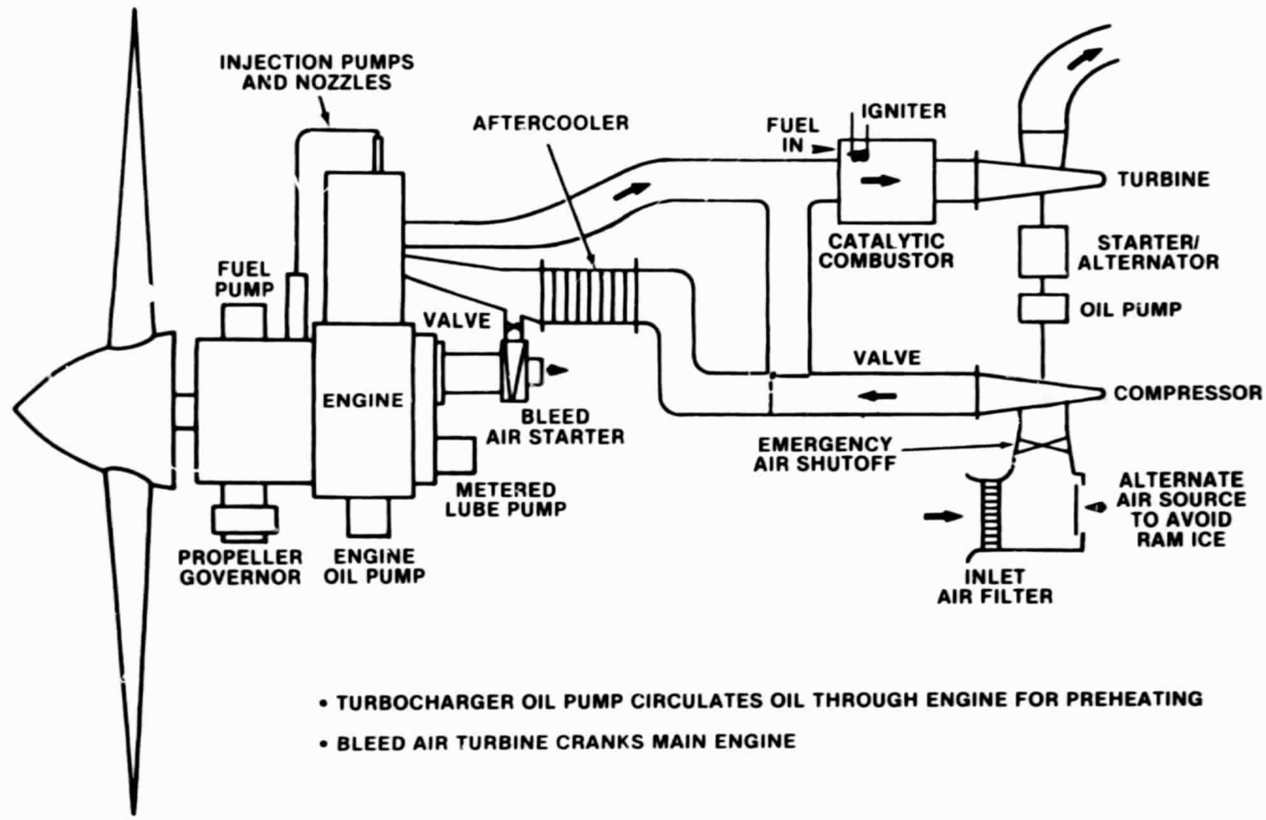
1. Max. power at takeoff
2. Max. power at 4570 m (15000 ft.)
3. Max. power at 7620 m (25000 ft.)
4. 65% power at 4570 m (15000 ft.)
5. 65% power at 7620 m (25000 ft.)

3.2.4 PROJECTION OF FUEL CONSUMPTION AND AVAILABLE TURBINE POWER

In order to conduct the cycle analysis calculations it is necessary to first establish the piston engine characteristics and the expected BSFC. To define these parameters a second simulation was made of the Napier Nomad engine performance using very advanced technologies including adiabatic operation. The numbers used are based on published test data (Reference 3).

1. Published performance data (Water-cooled):

Piston engine max. power	1983	kW	(2660 HP)
Excess turbine power	291	kW	(390 HP)
Compounded power	2274	kW	(3050 HP)
Compounded SFC	210	g/kWh	(.345 lb/HPh)
Fuel flow	477	kg/h	(1052 lb/h)
Piston engine BSFC	240	g/kWh	(.395 lb/HPh)
Energy input	81520	kcal/min	(323490 BTU/min)



- TURBOCHARGER OIL PUMP CIRCULATES OIL THROUGH ENGINE FOR PREHEATING
- BLEED AIR TURBINE CRANKS MAIN ENGINE

FIGURE 3-7 — SCHEMATIC 2-STROKE ENGINE WITH INDEPENDENT TURBO LOOP

2. Simulated performance with insulated cylinders:

Cylinder cooling requires approximately 13% of the energy input (TCM/GPD experience). Recovery of this energy in the turbine is approximately 55% or 406 kW (545 HP).

The excess turbine power becomes:

291 + 406 = 697 kW
(390 + 545 = 935 HP)

The compounded power becomes:

1983 + 697 = 2680 kW
(2660 + 935 = 3595 HP)

3. Further modification of this design by the use of radial cylinder configuration and reduced friction:

The mechanical efficiency of the original Nomad engine as published was 86%. This was assumed to improve to 90% due to a reduction of the number of cylinders and main bearings. Therefore,

Corrected engine power	2075 kW	(2783 HP)
Excess turbine power	697 kW	(935 HP)
Compounded power	2772 kW	(3718 HP)

4. Effect of very high injection pressures and electronic timing control:

High injection pressures result in improved atomization and better penetration and mixing with the air in the cylinder. A 5% improvement of the fuel consumption is expected from the improved combustion efficiency.

Corrected fuel flow	454 kg/h	(1000 lb/h)

5. The maximum cruise power performance of such a hypothetical Nomad engine thus would be:

Piston engine power	2075 kW	(2783 HP)
Excess turbine power	697 kW	(935 HP)
Compounded power	2772 kW	(3718 HP)
Fuel flow	454 kh/h	(1000 lb/h)
Piston engine BSFC	219 g/kWh	(.359 lb/HPh)
Compounded SFC	164 g/kWh	(.267 lb/HPh)

The turbine excess power thus would be 25% of the compounded power.

3.2.5 ENGINE CHARACTERISTICS AND CYCLE ANALYSIS DATA

In order to start the cycle calculations it is necessary to estimate the power of the piston engine. Using the analysis in Section 3.2.4 the engine power was chosen at 1118 kW (1500 HP). After several iterations of the cycle calculations the engine power was found to be 1342 kW (1803 HP). The end result of the calculations is shown in Table II. The average percentage of the excess turbine power is 21% which is reasonably close to the estimated 25% derived in Section 3.2.4.

TABLE II
1491 kW Operating Parameters

Altitude		Takeoff	100% Power		65% Power	
	m		4572	7620	4572	7620
	ft	Sea Level	15000	25000	15000	25000
1. PISTON ENGINE						
Engine Power	kW	1342	1257	887	839	623
	HP	1803	1685	1190	1125	835
Engine Speed	RPM	4000	4000	4000	3000	3000
Bore x Stroke	mm	122 x 135				
	in.	4.803 x 5.336				
Piston Speed	m/s	18.0	18.0	18.0	13.5	13.5
	fpm	3557	3557	3557	2668	2668
Number of Cylinders		8				
Displacement	ℓ	12.673				
	cu. in	773.36				
BMEP	bar	15.89	14.87	10.50	13.24	9.83
	psi	230.4	215.7	152.3	192.0	142.5
Engine BSFC	g/kWh	228.1	215.9	215.9	209.8	209.8
	lb/HPh	.375	.355	.355	.345	.345
Fuel Flow	kg/h	306	271	191	176	131
	lb/h	675	598	422	388	288
Ambient Press	bar	1.014	.572	.376	.572	.376
	psi	14.71	8.30	5.46	8.30	5.46
Ambient Temp	°C	15.9	− 14.5	− 34.3	− 14.5	− 34.3
	°F	60.0	5.3	− 30.4	5.3	− 30.4
Estimated Airspeed	kmh		696	691	561	568
	knots		376	373	303	307
	Mach		.60	.62	.48	.51
Stagn. Press	bar		.730	.488	.670	.447
	psi		10.59	7.08	9.71	6.48
Stagn. Temp.	°C		4.2	− 16.0	− 2.6	− 22.4
	°F		39.0	2.6	26.7	− 9.0
Compressor Press. Ratio		6.0:1	8.0:1	8.0:1	6.5:1	6.5:1
Int. Man. Press	bar	6.02	5.76	3.85	4.31	2.86
	psi	87.36	83.52	55.80	62.47	41.44
Int. Man. Temp	°C	245	263	235	224	188
	°F	472	504	454	435	370

TABLE II (Continued)
1491 kW Operating Parameters

Altitude	m / ft	Takeoff	100% Power		65% Power	
	m		4572	7620	4572	7620
	ft	Sea Level	15000	25000	15000	25000
Ratio $\frac{\text{Int. Man. Press.}}{\text{Exh. Man. Press.}}$		1.250	1.250	1.250	1.115	1.115
Exh. Man. Press	bar	4.82	4.61	3.08	3.86	2.56
	psi	69.89	66.82	44.64	56.02	37.17
Scavenge System		Schnuerle Loop Scavenging				
Height Int. Ports	mm			39		
	in			1.535		
Height Exh. Ports	mm			28		
	in			1.102		
Effective Compr. Ratio				9:1		
Nominal Compr. Ratio				12.25:1		
Nominal Piston Displ.	ℓ			1.841		
	cu. in			96.67		
Eff. Piston Displ.	ℓ			1.126		
	cu. in			68.74		
Scavenge Ratio	*			1		
Scavenge Efficiency	**			.725		
Charging Efficiency	***			.58		
Fuel Flow	kg/h	306	271	191	176	131
	lb/h	675	598	422	388	288
Compressor Air Flow	kg/s	3.41	3.15	2.22	1.94	1.38
	lb/s	7.52	6.95	4.89	4.28	3.04
Trapped Air Flow	kg/s	1.98	1.83	1.29	1.12	.80
	lb/s	4.36	4.03	2.84	2.48	1.76
Scavenge Air Flow	kg/s	1.43	1.32	.93	.82	.58
	lb/s	3.16	2.92	2.05	1.80	1.28
Air/Fuel Ratio-Trapped		23.4	24.4	24.0	23.0	22.0
Air/Fuel Ratio-Delivered		40.3	41.8	41.7	39.6	38.1

*Scavenge Ratio $R_s = \frac{W_{air\ delivered}}{V_{displ} \cdot d_1}$

**Scavenge Efficiency $\eta_{sc} = \frac{V_{trapped}}{V_1}$

***Charging Efficiency $\eta_{ch} = \frac{W_{trapped}}{V_{displ} \cdot d_1}$

TABLE II (Continued)
1491 kW Operating Parameters

Altitude		Takeoff	100% Power		65% Power	
	m / ft	Sea Level	4572 / 15000	7620 / 25000	4572 / 15000	7620 / 25000
Peak Firing Pressure	bar	164.8	156.3	105.0	118.9	79.9
	psi	2390	2267	1523	1725	1159
Peak Combustion Temp	°C	2244	2241	2181	2179	2135
	°F	4070	4066	3958	3953	3874
2. COMPRESSOR/TURBINE						
Compressor Air Flow	kg/s	3.41	3.15	2.22	1.94	1.38
	lb/s	7.52	6.95	4.89	4.28	3.04
Press. Ratio Compressor		6.0:1	8.0:1	8.0:1	6.5:1	6.5:1
Adiab. Compr. Eff.		.87	.86	.86	.87	.87
Polytr. Compr. Eff.		.90	.89	.89	.90	.90
Compr. Discharge Temp.	°C	245	263	235	224	188
	°F	472	504	454	435	370
Compressor Power	kW	792	825	564	445	295
	HP	1061	1106	756	597	395
Bearing Loss	kW	7	7	6	4	3
	HP	10	10	8	6	4
Compr. + Bearings	kW	799	832	570	450	298
	HP	1071	1116	764	603	399
Turbine Gas Flow	kg/s	3.50	3.23	2.27	1.99	1.42
	lb/s	7.71	7.12	5.01	4.38	3.12
Turbine Inlet Temp	°C	595	603	575	581	553
	°F	1103	1117	1067	1077	1026
Press. Ratio Turbine		4.73:1	8.00:1	8.10:1	6.72:1	6.76:1
Adiab. Turbine Eff.		.89	.88	.88	.89	.89
Turbine Power	kW	990	1146	785	651	450
	HP	1328	1537	1053	873	603
Excess Turbine Power	kW	191	314	215	201	152
	HP	257	421	289	270	204
Net Prop. Power	kW	1491	1491	1033	969	708
	HP	2000	2000	1385	1300	950
Fuel Flow	kg/h	306	271	191	176	131
	lb/h	675	598	422	388	288

TABLE II (Continued)
1491 kW Operating Parameters

	Takeoff	100% Power		65% Power	
Altitude m / ft	Sea Level	4572 / 15000	7620 / 25000	4572 / 15000	7620 / 25000
Compound SFC with Accessory Power g/kWh	205	182	185	182	185
lb/HPh	.338	.298	.303	.298	.303
$\frac{\text{Excess Turbine Power}}{\text{Net Prop. Power}} \times 100\%$	12.8	21.1	20.8	20.7	21.5
Compound Power W/O Accessory Power kW	1513	1547	1089	1025	764
HP	2030	2075	1460	1375	1025
SFC W/O Accessory Power g/kWh	202	175	175	172	171
****lb/HPh	.332	.288	.289	.282	.281

****The SFC without accessory power is a true representation of the fuel economy of the basic power plant.

The Figures 3-8 through 3-12 show the compounded power schematics for the five flight conditions calculated above.

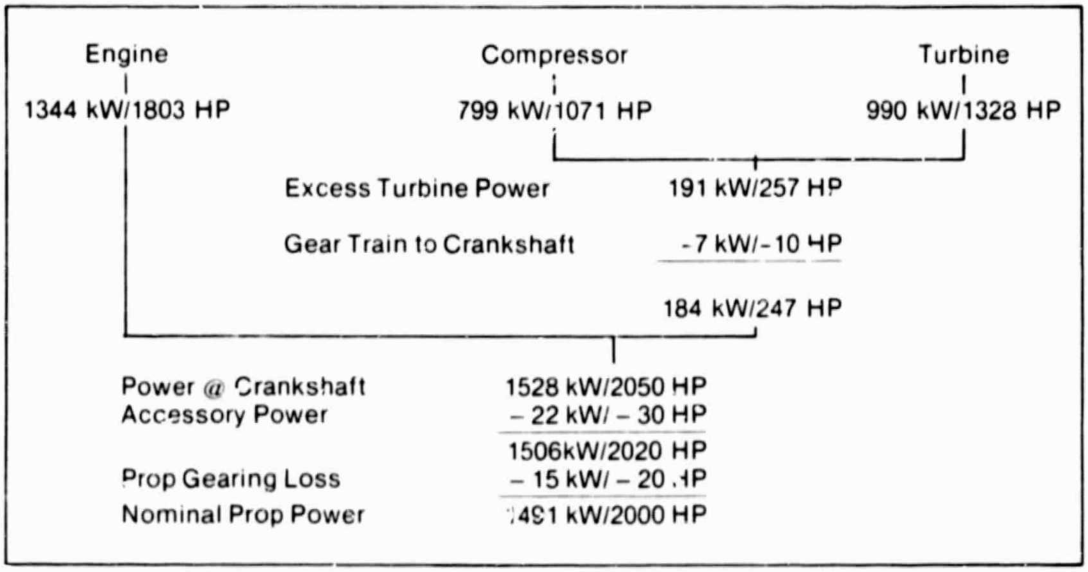


FIGURE 3-8 — POWER SCHEMATIC TAKEOFF MODE

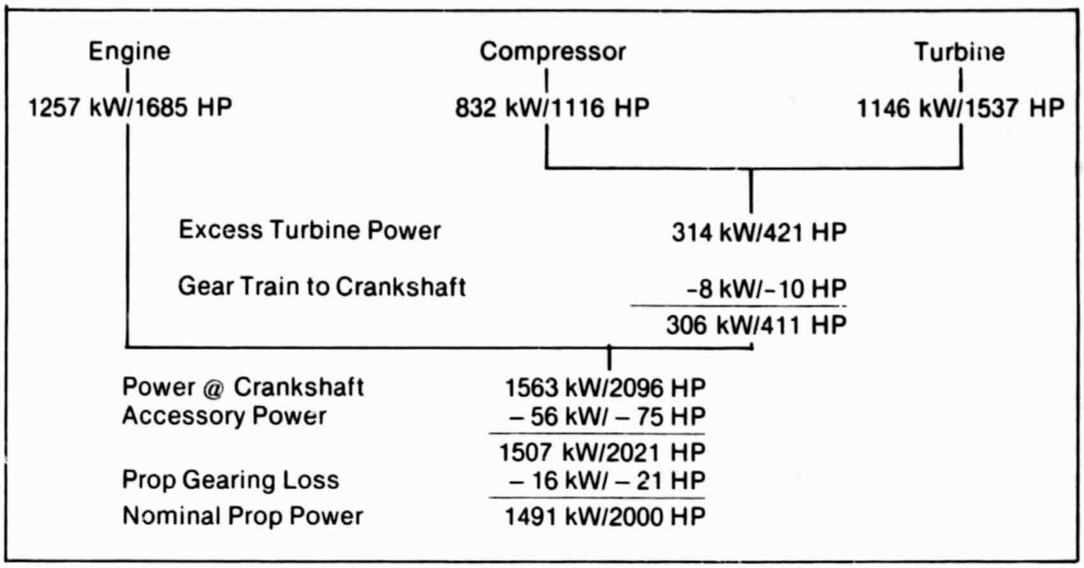


FIGURE 3-9 — POWER SCHEMATIC 100% CRUISE POWER @ 4572m (15000 FT.) ALTITUDE

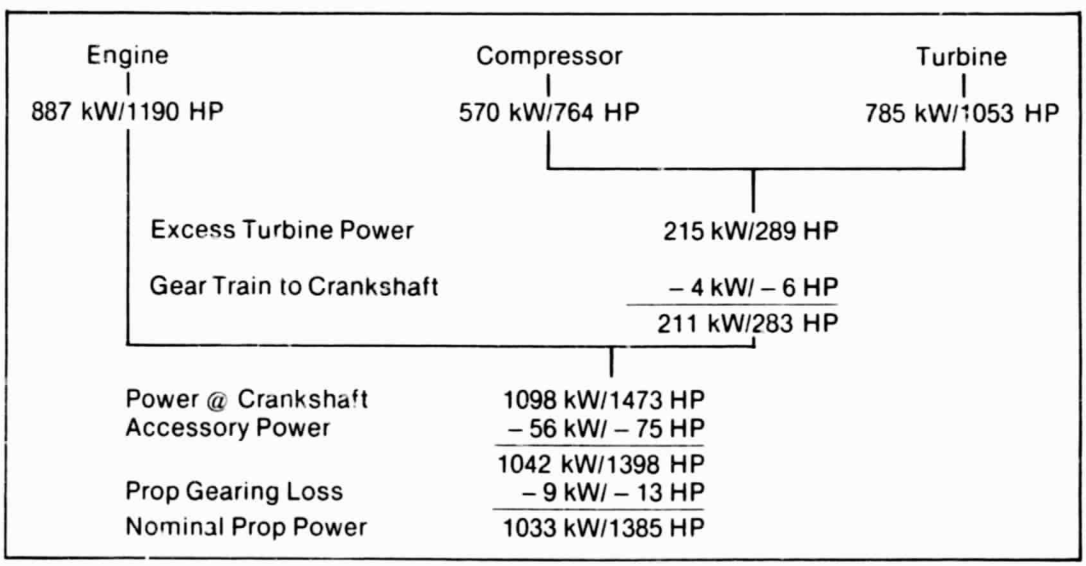


FIGURE 3-10 — POWER SCHEMATIC 100% CRUISE POWER @ 7620m (25000 FT.) ALTITUDE

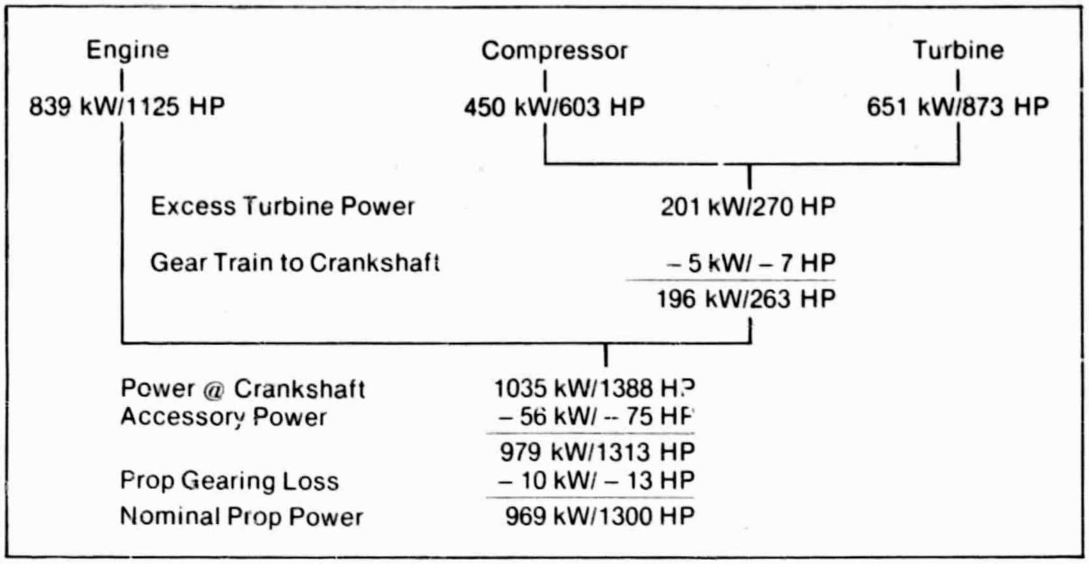


FIGURE 3-11 — POWER SCHEMATIC 65% CRUISE POWER @ 4572m (15000 FT.) ALTITUDE

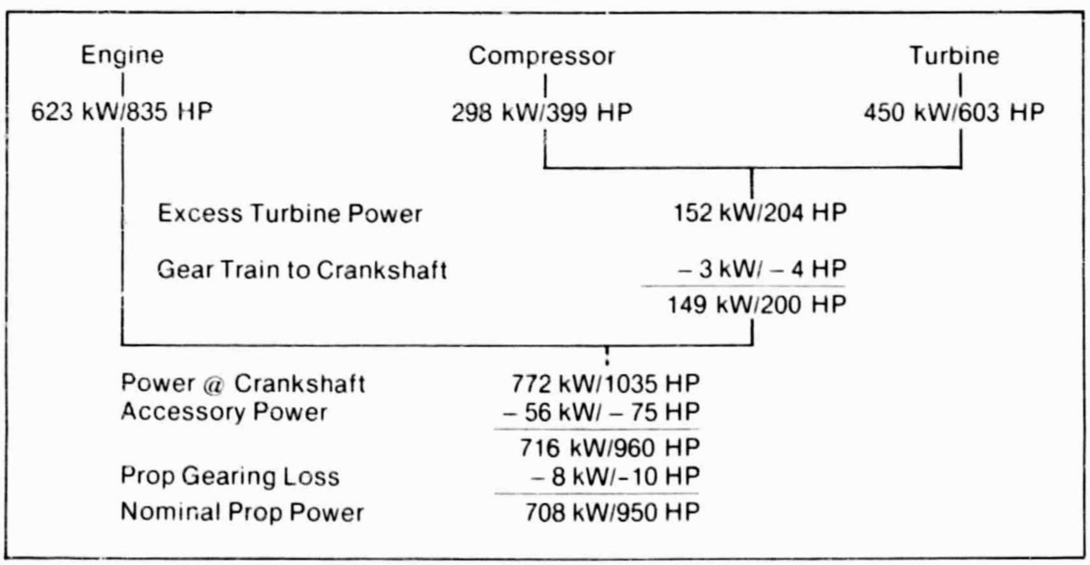


FIGURE 3-12 — POWER SCHEMATIC 65% CRUISE POWER @ 7620m (25000 FT.) ALTITUDE

3.2.6 EFFECT OF AIR AFTERCOOLING ON ENGINE PERFORMANCE

A study was made to investigate the effect of the aftercooler in the proposed engine configuration. The general purpose of an aftercooler is to reduce the temperature of the air out of the compressor and thus increase the induction air density in the intake manifold. However, the same density effect can be obtained without aftercooling by an increase of the intake manifold pressure. Table III shows a comparison of operation with and without an aftercooler for the 100% power condition at 4572m (15000 ft.) altitude for the same engine.

Common parameters are engine fuel flow and air density in the intake manifold.

TABLE III
Effect of Aftercooling on an Adiabatic Cycle

		No Aftercooling	With Aftercooling
Piston Engine Displacement	l	12.673	12.673
	cu. in.	773.36	773.36
Fuel Flow	kg/h	271	271
	lb/h	598	598
Compressor Inlet Press.	bar	.72	.72
	psi	10.44	10.44
Compressor Inlet Temp	°C	4	4
	°F	39	39
Compressor Pressure Ratio		8.00:1	5.91:1
Compressor Discharge Press.	bar	5.76	4.26
	psi	83.52	61.73
Compressor Discharge Temp.	°C	263	225
	°F	504	436
Press. Drop In Aftercooler	bar		.04
	psi		.58
Intake Manifold Press.	bar	5.76	4.22
	psi	83.52	61.15
Temp. Drop in Aftercooler	°C		109
	°F		196
Intake Manifold Temp	°C	229	116
	°F	504	240
Intake Manifold Density	kg/	.00375	.00378
	lb/cu. ft	.234	.236
Air/Fuel Ratio — Trapped		24.4	24.4
Max. Combustion Press	bar	156.31	118.66
	psi	2267	1721

TABLE III (Continued)
Effect of Aftercooling on an Adiabatic Cycle

		No Aftercooling	With Aftercooling
Max. Combustion Temp.	°C	2241	1853
	°F	4066	3367
IMEP	bar	16.57	15.81
	psi	240.3	229.3
BMEP	bar	14.87	14.23
	psi	215.7	206.4
Piston Engine Power	kW	1257	1204
	HP	1685	1615
Piston Engine BSFC	g/kWh	216	225
	lb/HPh	.355	.370
Compressor Air Flow	kg/s	3.15	3.15
	lb/s	6.95	6.95
Compressor Power	kW	832	711
	HP	1116	954
Turbine Press. Ratio		8.00:1	5.85:1
Turbine Inlet Temp.	°C	603	435
	°F	1117	814
Turbine Gas Flow	kg/s	3.23	3.23
	lb/s	7.12	7.12
Turbine Power	kW	1146	817
	HP	1537	1095
Excess Turbine Power	kW	314	105
	HP	421	141
Piston Engine Power	kW	1257	1204
	HP	1685	1615
Losses & Accessory Power	kW	79	72
	HP	106	96
Nominal Propeller Power	kW	1491	1238
	HP	2000	1660
Aftercooler Cooling Loss	kcal/min		5004
	BTU/min		19858
Heat Recovery Rate in Turbine	%		55
Equivalent Cooling Power	kW		192
	HP		257

The loss of compounded engine power in the case of an aftercooled engine (1238 vs. 1491 kW) is largely accounted for by the reduction of energy in the air in the aftercooler (192 kW). It shows that better overall fuel economy is obtained without aftercooling (with uncooled cylinders) and turbocompounding.

Other conclusions that follow from this analysis are:

1. The non-aftercooled cycle requires a higher compressor pressure ratio in order to obtain the same engine air flow.

2. The non-aftercooled cycle results in higher firing pressures.

3. The non-aftercooled cycle results in higher combustion temperatures due to the higher induction air temperature and thus may require different cylinder and piston top materials.

4. The reduced compounded power of the aftercooled cycle (1238 vs. 1491 kW) must be compensated for by a larger piston engine and turbine in order to develop the same overall power.

3.2.7 ALTITUDE PERFORMANCE DATA UP TO 7620m (25000 FT.)

1. Performance summary.

   Table IV is a summary of the performance data shown in Table II.

TABLE IV
Summarized 1491 kW Performance Parameters

		Takeoff	100% Power		65% Power	
Altitude	m ft	Sea Level	4572 15000	7620 25000	4572 15000	7620 25000
Assumed Airspeed	km/h		696	691	561	568
	knots		376	373	303	307
	Mach. No.		.60	.62	.48	.51
Nominal Prop Power	kW	1491	1491	1033	969	708
	HP	2000	2000	1385	1300	950
Prop Speed	*RPM	1615	1615	1615	1211	1211
Engine Speed	RPM	4000	4000	4000	3000	3000
Fuel Flow	kg/h	306	271	191	176	131
	lb/h	675	598	422	388	288
Compounded BSFC	g/kWh	205	182	185	182	185
	lb/HPh	.338	.299	.305	.298	.303

*The choice of the propeller speed is based on a propeller tip speed at .8M and a diameter of 3.05m (10 ft.).

The sonic velocity at 4572m (15000 ft.) is 322.5 m/s (1058 fps)

Propeller tip speed = 258 m/s (846.5 fps)
Propeller speed = 1615 RPM at 4000 engine RPM
Propeller gear reduction = 2.477:1

2. Propeller shaft horsepower versus engine speed and altitude.

A. Full load prop torque at sea level.

The following part load performance data are based on full load engine power, i.e., the maximum power that the power plant can produce at any engine speed. Two typical points on the torque curve are:

- The rated torque which is the maximum torque at 4000 engine RPM.
- The maximum torque, which is estimated to be 5% above the rated torque and occurs at 75% of the rated speed (3000 RPM).

The torque and power values are shown in Table V.

TABLE V
Full Load Power at Sea Level

Engine RPM	Propeller RPM	Propeller Torque N.m	Propeller Torque Ft. Lb.	Propeller Power kW	Propeller Power HP
4000	1615	8819	6504	1491	2000
3500	1413	9149	6747	1353	1815
3000	1211	9270	6836	1175	1576
2500	1009	9068	6687	958	1285

B. Altitude effect.

The engine is flat rated (constant power) from sea level to 4572m (15000 ft.). This altitude was a study guideline. The flat rating could have been designed up to higher altitudes since the turbocompressor is not a limiting factor.

The power above 4572m is reduced due to the specific design of the turbine machinery. The maximum obtainable power at 7620m (25000 ft.) is 887 kW (1190 HP).

Table VI and Figure 3-13 show the maximum power at sea level and altitude at various engine speeds.

TABLE VI
Full Load Power at Sea Level and Altitude

RPM		Propeller Power					
Engine	Prop	Sea Level		4572m (15000 ft)		7620m (25000 ft)	
		kW	HP	kW	HP	kW	HP
4000	1615	1491	2000	1491	2000	1033	1385
3500	1413	1353	1815	1353	1815	937	1257
3000	1211	1175	1576	1175	1576	814	1091
2500	1009	958	1285	958	1285	664	890

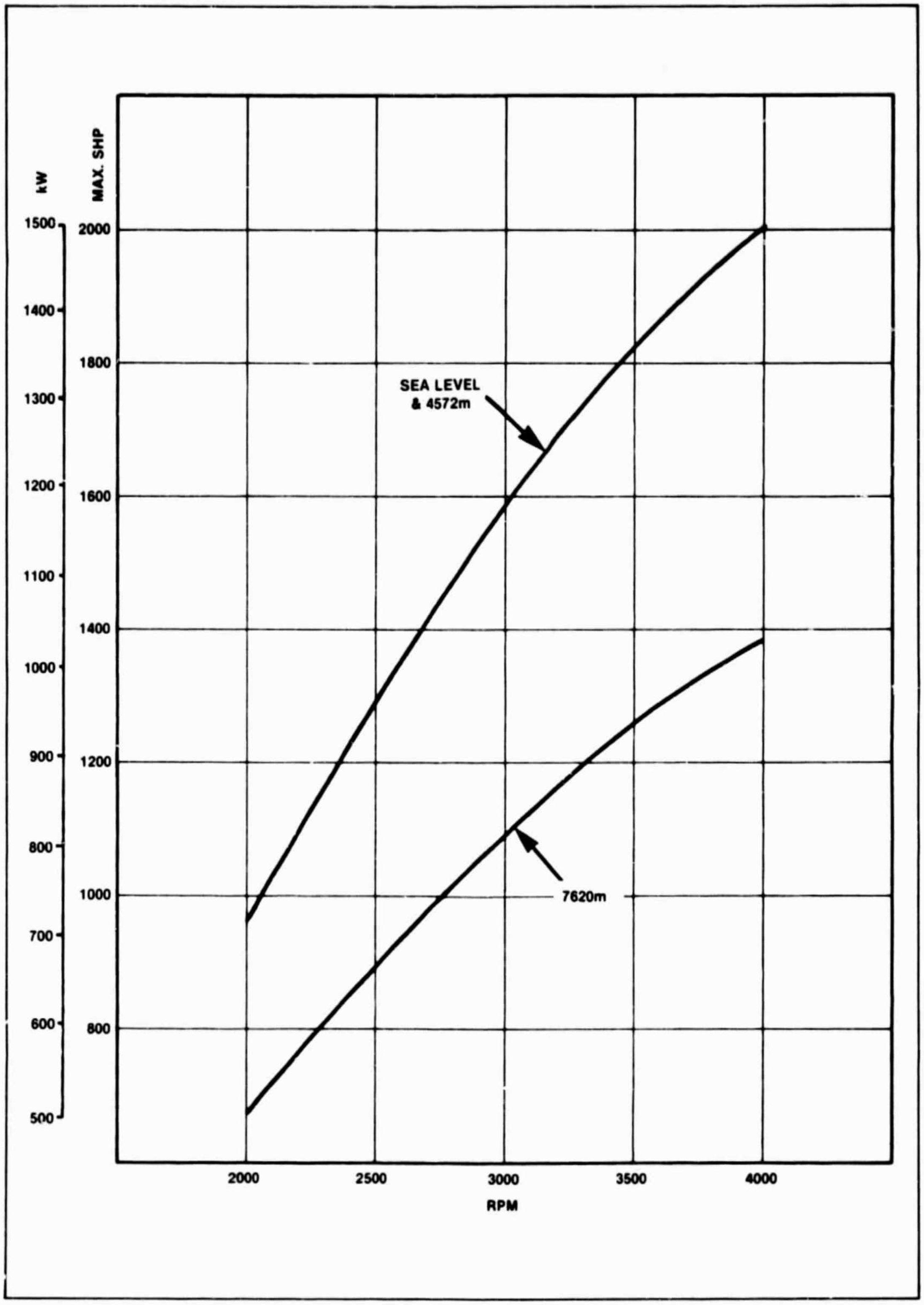


FIGURE 3-13 — 1491 kW COMMUTER AIRCRAFT DIESEL MAXIMUM SHP VERSUS RPM

C. Fuel flow vs. RPM and altitude.

Table VII shows the sea level fuel flows at maximum power at various engine speeds.

- The propeller powers were taken from Table VI.
- The crankshaft power at 4000 RPM is taken from Figure 3-8. A correction was made for reduced gearing losses at lower engine speeds.
- The net turbine power at 4000 engine RPM is taken from Figure 3-8. The optimum turbine match was arbitrarily selected at peak 1491 kW (2000 HP) power but could have been chosen at a different load point. Lower turbine efficiencies at lower engine speeds thus result in a reduced contribution of the turbine power to the overall power. This contribution becomes negative below 2500 engine RPM, i.e., a part of the piston engine power will be required to drive the compressor.
- The piston engine BSFC and the fuel flow at 4000 RPM are taken from Table II. Part load test data of the TCM/GPD AVCR 1360 air-cooled diesel engine were used to proportion the BSFC's at lower engine speeds and loads.

TABLE VII
Fuel Flow at Sea Level at Max. SHP

RPM	Prop kW HP	Cranksh. kW HP	Turbine % Total	Turbine Net kW HP	Engine kW HP	Piston Engine BSFC g/kWh lb/HPh	Fuel Flow kg/h lb/h	Compounded BSFC g/kWh lb/HPh
4000	1491	1528	12.5	184	1344	228	306	205
	2000	2050		247	1803	.375	675	.338
3500	1353	1393	9.0	125	1268	219	278	205
	1815	1868		168	1700	.360	612	.337
3000	1175	1213	5.0	60	1153	216	249	212
	1576	1627		81	1546	.355	549	.348
2500	958	994	0	0	994	219	218	228
	1285	1333			1333	.360	480	.374

The fuel flows at 4572m (15000 ft.) and 7620m (25000 ft.) altitude are shown in the Tables VIII and IX and were derived in a similar manner to that for sea level.

TABLE VIII
Fuel Flow at 4572m (15000 ft.) at Max. SHP

RPM	Prop kW HP	Cranksh. kW HP	Turbine % Total	Turbine Net kW HP	Engine kW HP	Piston Engine BSFC g/kWh lb/HPh	Fuel Flow kg/h lb/h	Compounded BSFC g/kWh lb/HPh
4000	1491	1563	19.6	306	1257	216	271	182
	2000	2096		411	1685	.355	598	.299
3500	1353	1423	18.0	256	1167	213	249	184
	1815	1908		343	1565	.350	548	.302
3000	1175	1243	16.0	199	1044	213	222	189
	1576	1667		267	1400	.350	490	.311
2500	958	1024	13.0	133	891	219	195	204
	1285	1373		178	1195	.360	430	.335

TABLE IX
Fuel Flow at 7620m (25000 ft.) at Max. SHP

RPM	Prop kW HP	Cranksh. kW HP	Turbine % Total	Turbine Net kW HP	Engine kW HP	Piston Engine BSFC g/kWh lb/HPh	Fuel Flow kg/h lb/h	Compounded BSFC g/kWh lb/HPh
4000	1033	1098	19.2	211	887	216	191	185
	1385	1473		283	1190	.355	422	.305
3500	937	1003	17.5	175	828	207	171	182
	1257	1345		235	1110	.340	377	.300
3000	814	878	15.5	136	742	207	153	188
	1091	1177		182	995	.340	338	.310
2500	664	726	12.5	91	635	213	135	203
	890	974		122	852	.350	298	.335

Note that the contribution of the turbine power to the overall power is higher at altitudes above sea level. This is due to the ram effect at the compressor inlet which reduces the required compressor power and to the lower ambient air pressure which results in increased turbine power.

Figure 3-14 shows fuel flows from the Tables VII, VIII and IX in graphical form.

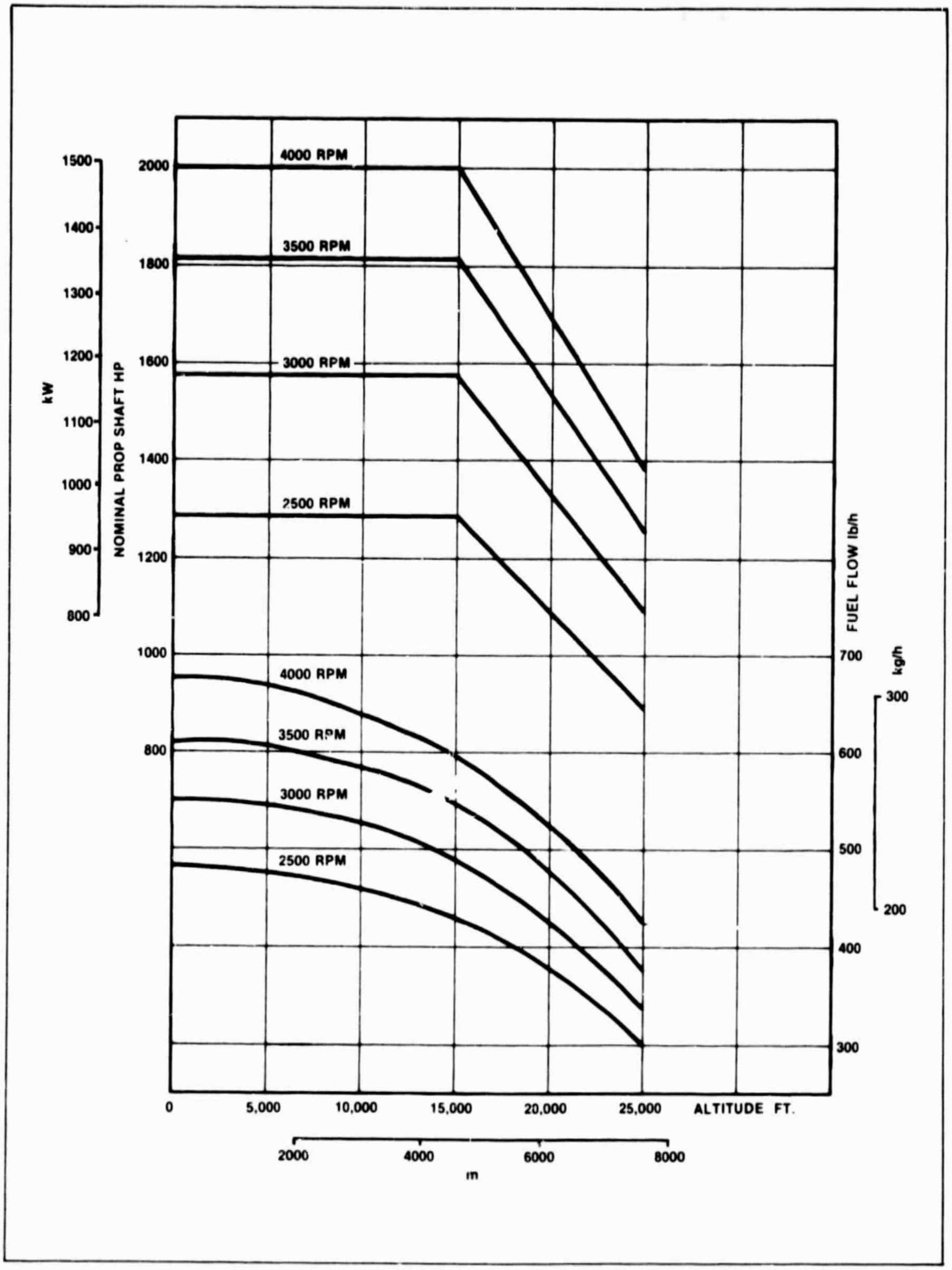


FIGURE 3-14 — 1491 kW COMMUTER AIRCRAFT DIESEL MAXIMUM SHP AND FUEL FLOW

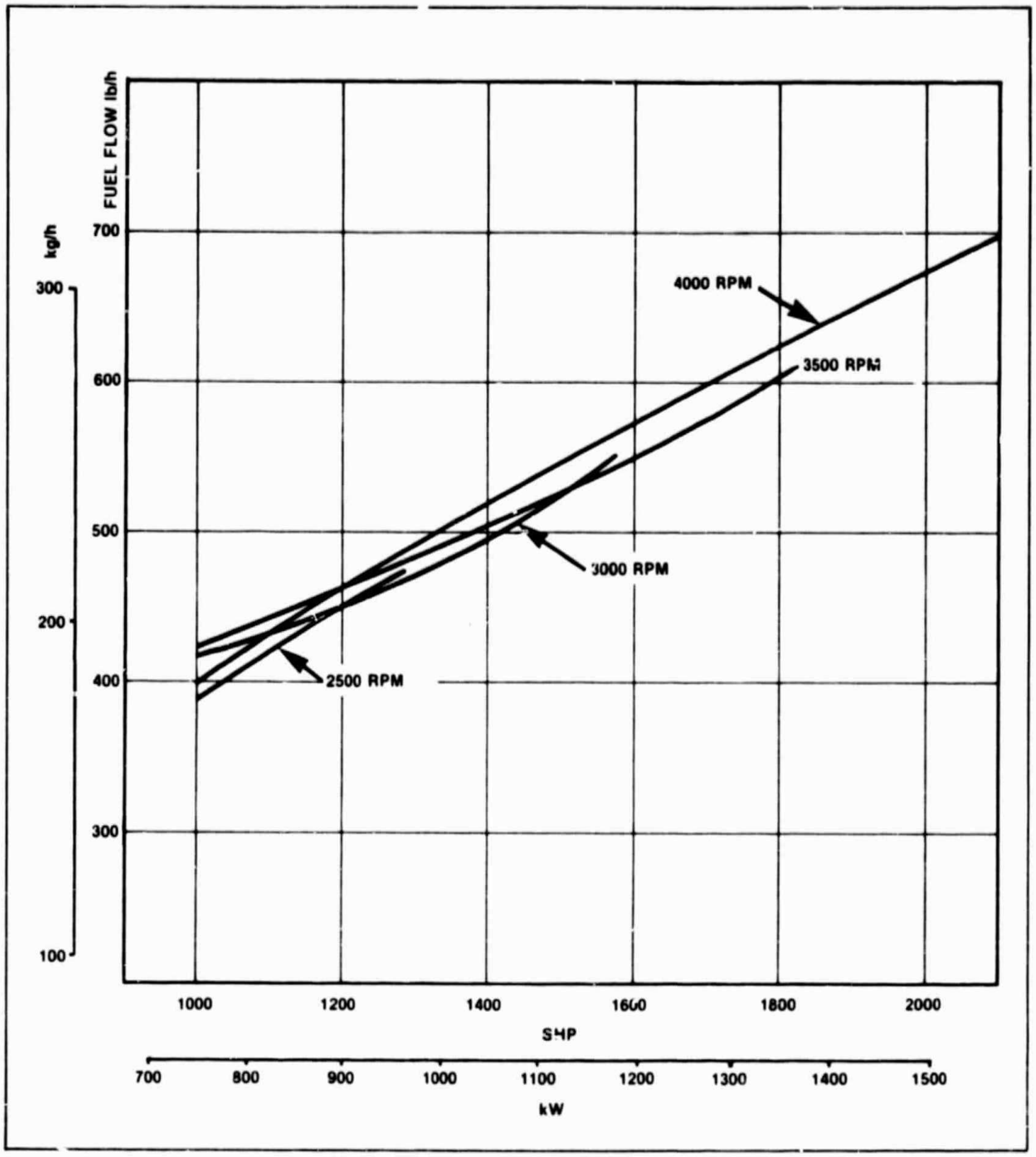


FIGURE 3-15 — 1491 kW COMMUTER AIRCRAFT DIESEL PART LOAD FUEL CONSUMPTION AT SEA LEVEL

3. Estimated fuel flow at idle RPM.

The values shown below are estimates of the idle fuel flow.

Idle Speed	1000	RPM
FMEP	1.38	bar (20 psi)
Friction Power	29	kW (39 HP)
Friction SFC	487	g/kWh (.80 lb/HPh)
Idle Fuel Flow	14	kg/h (31 lb/h)

If 22 kW (30 HP) accessory power is included:

Engine Power	51	kW (69 HP)
BSFC	456	g/kWh (.75 lb/HPh)
Fuel Flow	24	kg/h (52 lb/h)

4. Full and part load power settings.

A. Takeoff power at 32.5°C (90°F).

The previous power calculations are based on 15.0°C (59°F) ambient air temperature.

The power reduction of diesel engines due to elevated air temperatures is 1% per 5.56°C (10°F). Thus the corrected gross crankshaft power at 90°F (see Figure 3-8) is:

.969 x 1528	= 1481 kW (1986 HP)
Losses & Accessory Power	= 37 kW (− 50 HP)
Nominal Prop Power	= 1444 kW (1936 HP)

B. Maximum climb power at ISA ambient conditions* — see Table VI.

- The power plant is flat rated at 1491 kW (2000 SHP) up to 4572m (15000 ft.) altitude.

- Above 4572m (15000 ft.) the climb power will decrease linearly with altitude from 1491 kW (2000 HP) to 1033 kW (1385 HP) at 7620m (25000 ft.)

C. Partial power @ ISA ambient conditions.

The fuel flows were determined for the following power settings:

#1 50% @ ISA conditions.
#2 60% @ ISA conditions.
#3 70% @ ISA conditions.
#4 80% @ ISA conditions.
#5 90% @ ISA conditions.

*ISA — International Standard Atmosphere
— Pressure 1.013 bar (29.92 in Hg)
— Temperature 15°C (59°F)

The Figures 3-15 through 3-17 show the fuel flows as a function of the nominal propeller power, engine RPM and altitude. The end points of the curves represent the 100% power setting for that engine speed and altitude.

The RPM curves are too close together to draw conclusions on the optimum engine speed for a given power level.

3.3 Engine Physical Characteristics

A study was made of the engine weight, center of gravity and the overall dimensions.

3.3.1 ENGINE WEIGHT ANALYSIS

A weight analysis was conducted of two versions of materials for the same engine performance. One version uses conventional materials and the second uses advanced lightweight material technologies.

A detailed weight analysis of the two versions is shown in Table X.

TABLE X
1491 kW (2000 HP) Weight Analysis

	Weight			
	Advanced		Conventional	
Component	kg	lb	kg	lb
Prop Gear Housing	19	41	23	51
Crankshaft	33	73	33	73
Prop Drive Gear	9	20	10	22
Pinions	18	40	20	44
Sun Gear on Crankshaft	3	7	3	7
Cylinders	91	200	91	200
Pistons	33	72	44	96
Piston Pins	9	20	9	20
Connecting Rods	24	52	39	85
Crankcase	15	32	18	40
Intake Manifolds	18	40	23	50
Exhaust Manifolds	17	38	17	38
Accessory Drive Gears	4	9	5	10
Injection System	36	80	36	80
Governor	1	3	1	3
Vacuum Pump	1	3	1	3
Oil Pump	5	12	6	13
Starter	27	60	27	60
Generator	27	60	27	60
Oil Cooler	14	30	14	30
Compressor/Turbine	114	250	145	320
Turbine Drive Gearing	23	50	27	60
Balance of Parts	49	108	61	135
Engine Weight — Dry	590	1300	680	1500
Oil & Tank Weight	30	65	30	65
Engine Weight — Wet	620	1365	710	1565

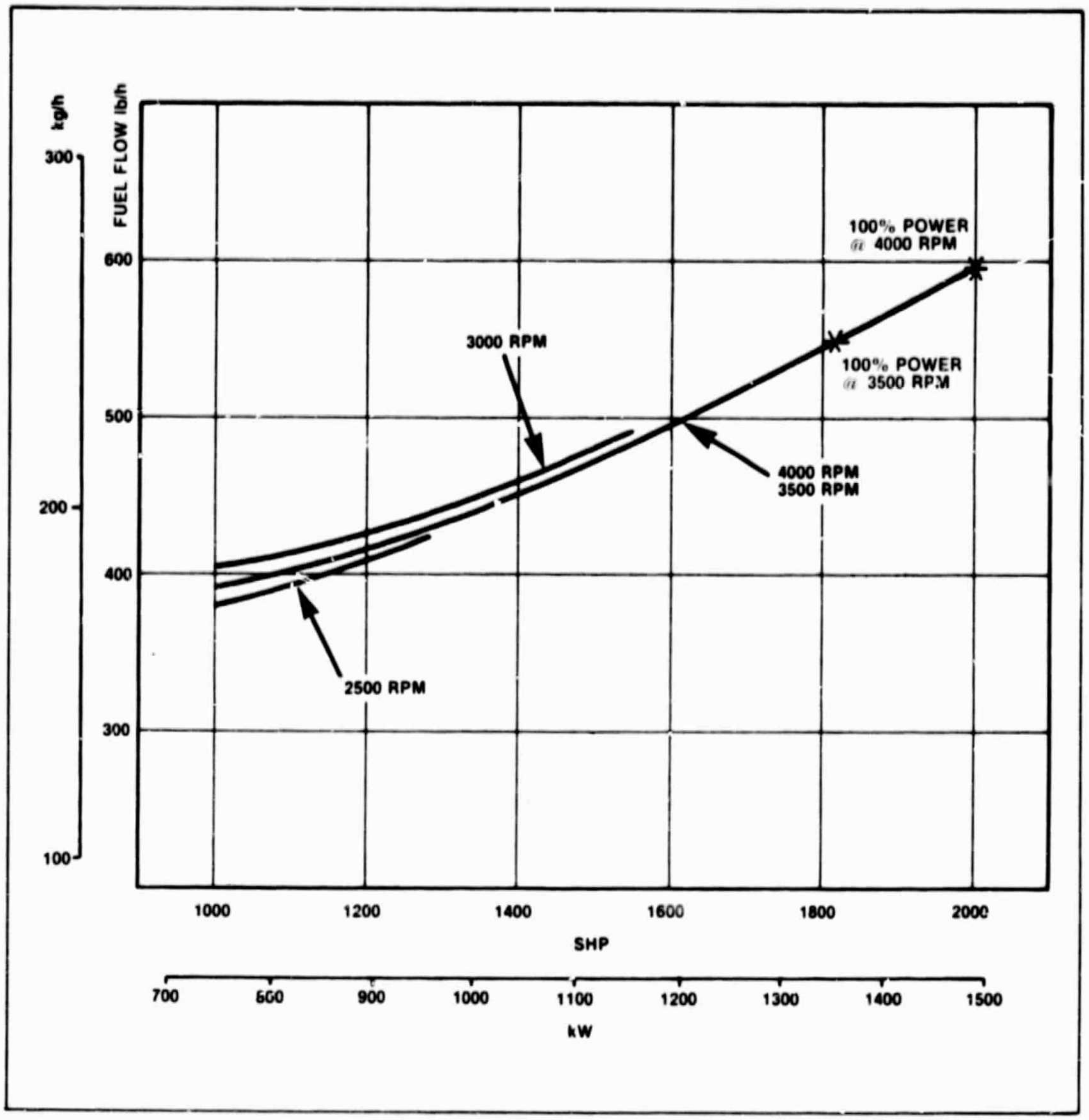


FIGURE 3-16 — 1491 kW COMMUTER AIRCRAFT DIESEL PART LOAD FUEL CONSUMPTION AT 4572m ALTITUDE

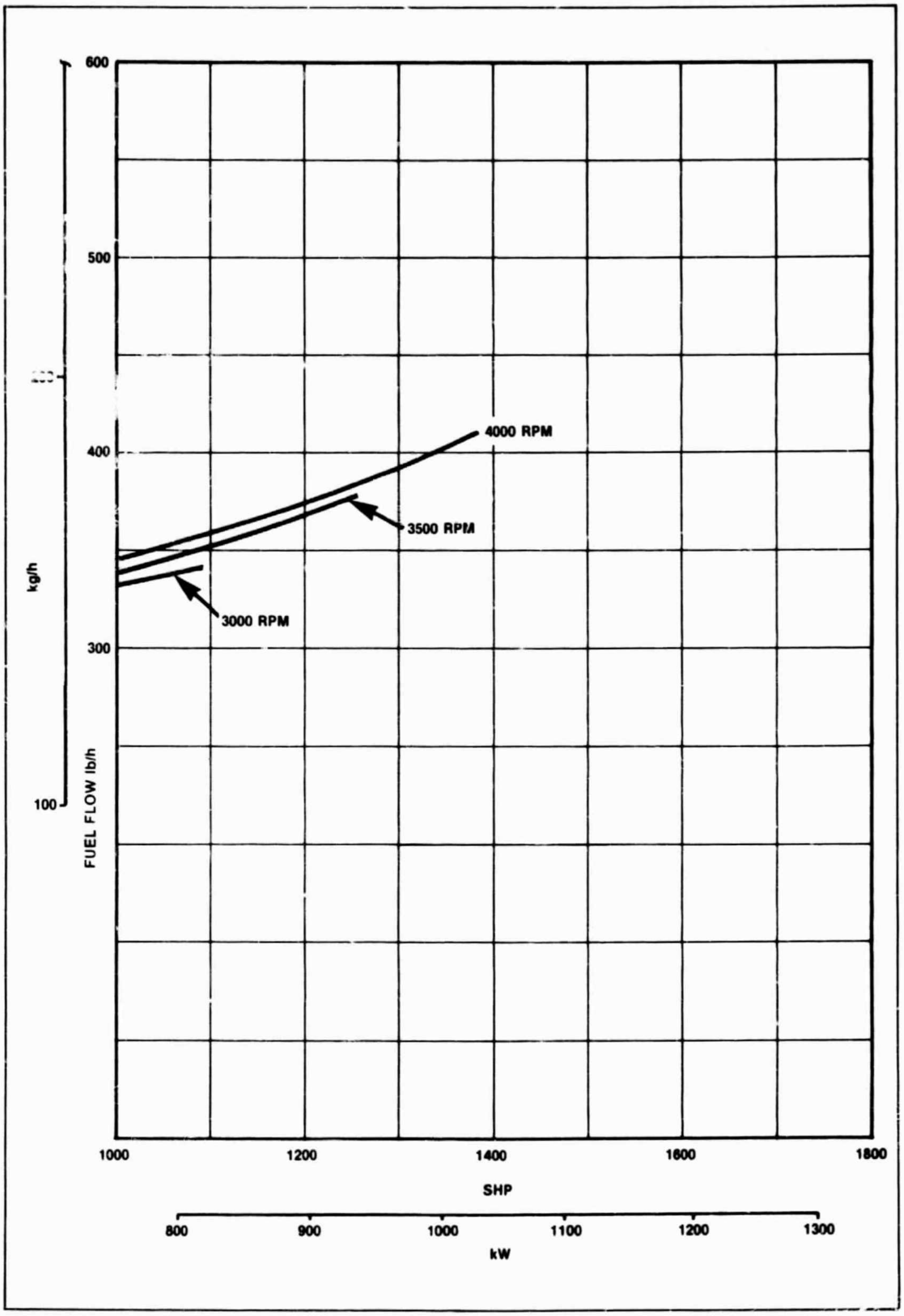


FIGURE 3-17 — 1491 kW COMMUTER AIRCRAFT DIESEL PART LOAD FUEL CONSUMPTION AT 7620m ALTITUDE

The specific weights, referenced to 1491 kW (2000 HP) net shaft power are:

	kg/kW	lb/HP
Advanced Materials	.415	.683
Conventional Materials	.476	.783

These numbers, although higher than for a turboprop engine, are extremely low for a diesel power plant. By comparison, the specific weight of the relatively low weight Napier Nomad engine was .71 kg/kW (1.17 lb/HP).

3.3.2 LOCATION OF THE ENGINE CENTER OF GRAVITY

The center of gravity was determined in two directions. It is assumed to be on the vertical axis of the engine.

1. Horizontally.

   154mm (6.08") behind the centerline of the front row of cylinders.

2. Vertically.

   87mm (3.44") below the crankshaft centerline.

3.3.3 ENGINE DIMENSIONS

The overall engine dimensions are:

Length	1490mm	(58.62 in)
Width	752mm	(29.58 in)
Height	900mm	(35.41 in)
Volume	1006dm^3	(35.53 ft^3)
Frontal Area	5026cm^2	(799 in^2)

4.0 DESIGN STUDY OF THE 895 kW (1200 SHP) ENGINE

This engine is essentially a scaled down version of the 1491 kW (2000 HP) engine. Its features are:

- 6 cylinders in a two row, radial configuration.
- A high crankshaft speed
- Two-stroke cycle — Schnuerle scavenge system
- Insulated cylinders
- Turbocompounded
- No aftercooling
- 9:1 effective compression ratio
- Variable speed drive between turbine and piston engine
- High pressure injection system
- Open chamber combustion system
- Geared propeller drive
- Electronic controls

4.1 Engine Concept Design

Three views and a partial section of the engine are shown in Figures 4-1 through 4-4.

The cylinders are arranged in two rows of three cylinders each. Two cylinders are shown upright in a vertical plane, the remaining cylinders are at a 30° angle with the horizontal plane. The engine has a very favorable profile with the turbomachinery located between two banks of cylinders. It was again decided, due to the high firing pressures, to design a crankshaft with two separate crank throws.

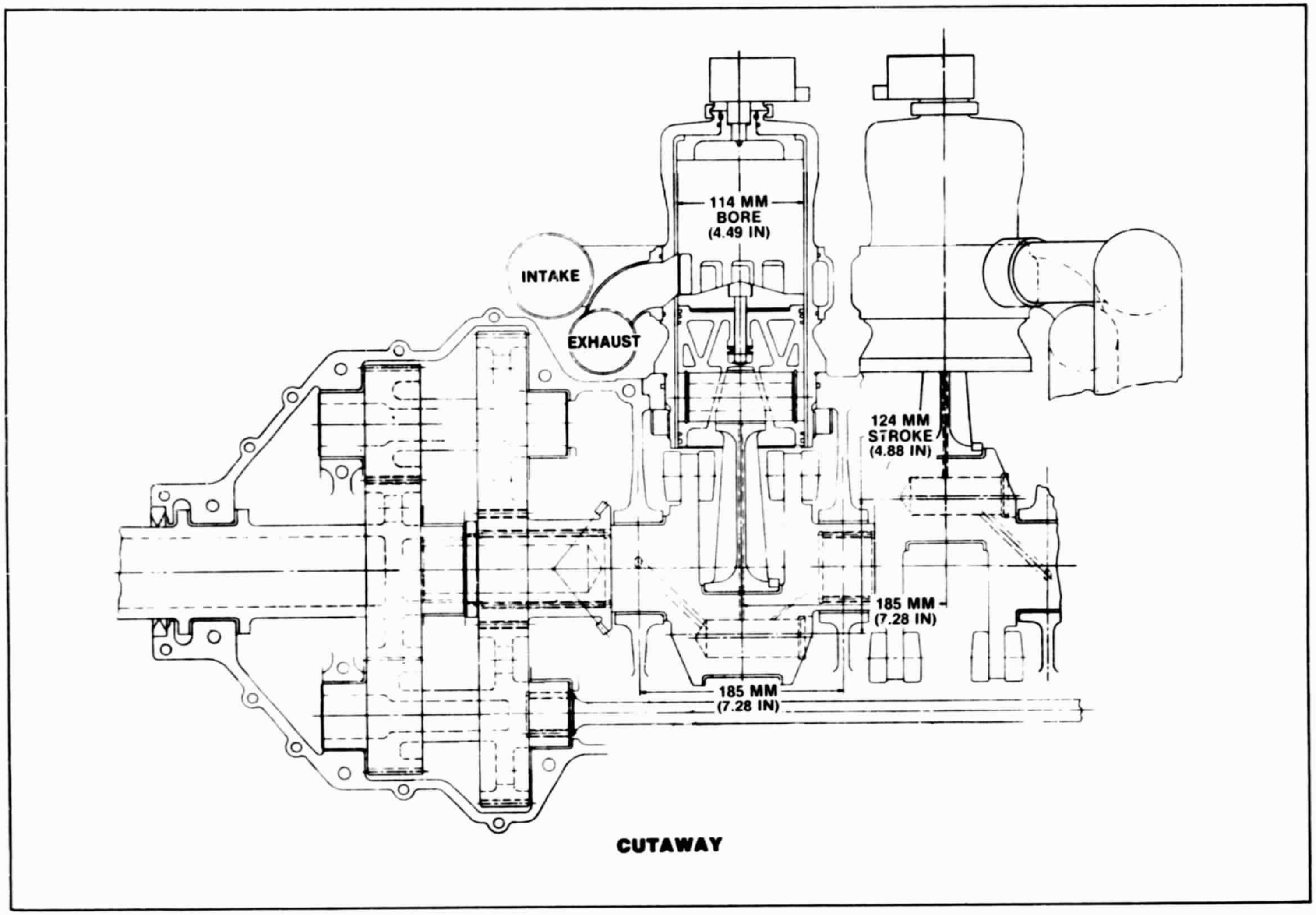


FIGURE 4-1 — 895 kW COMMUTER AIRCRAFT DIESEL - PARTIAL LONGITUDINAL SECTION

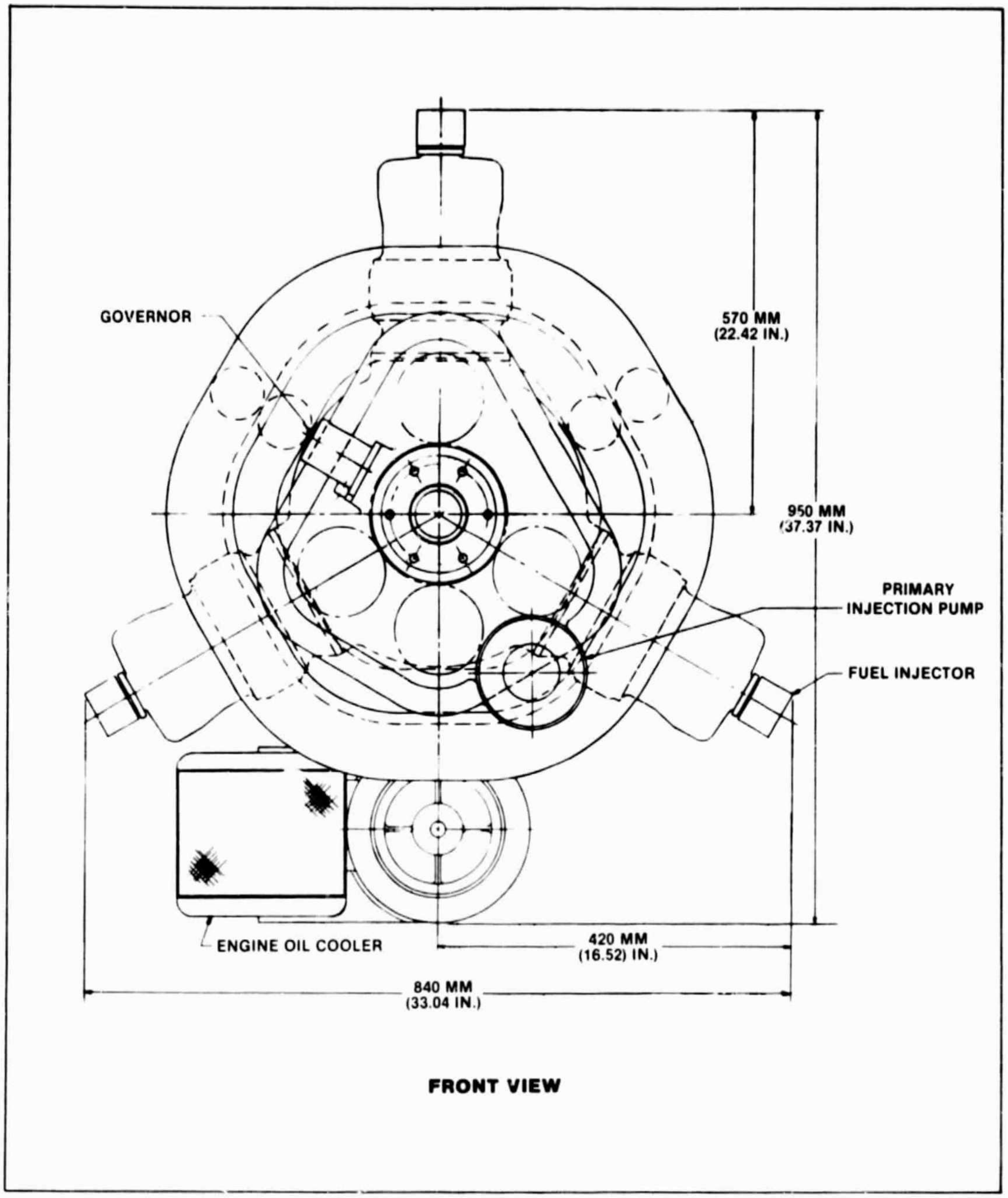


FIGURE 4-2 — 895 kW COMMUTER AIRCRAFT DIESEL - FRONT VIEW

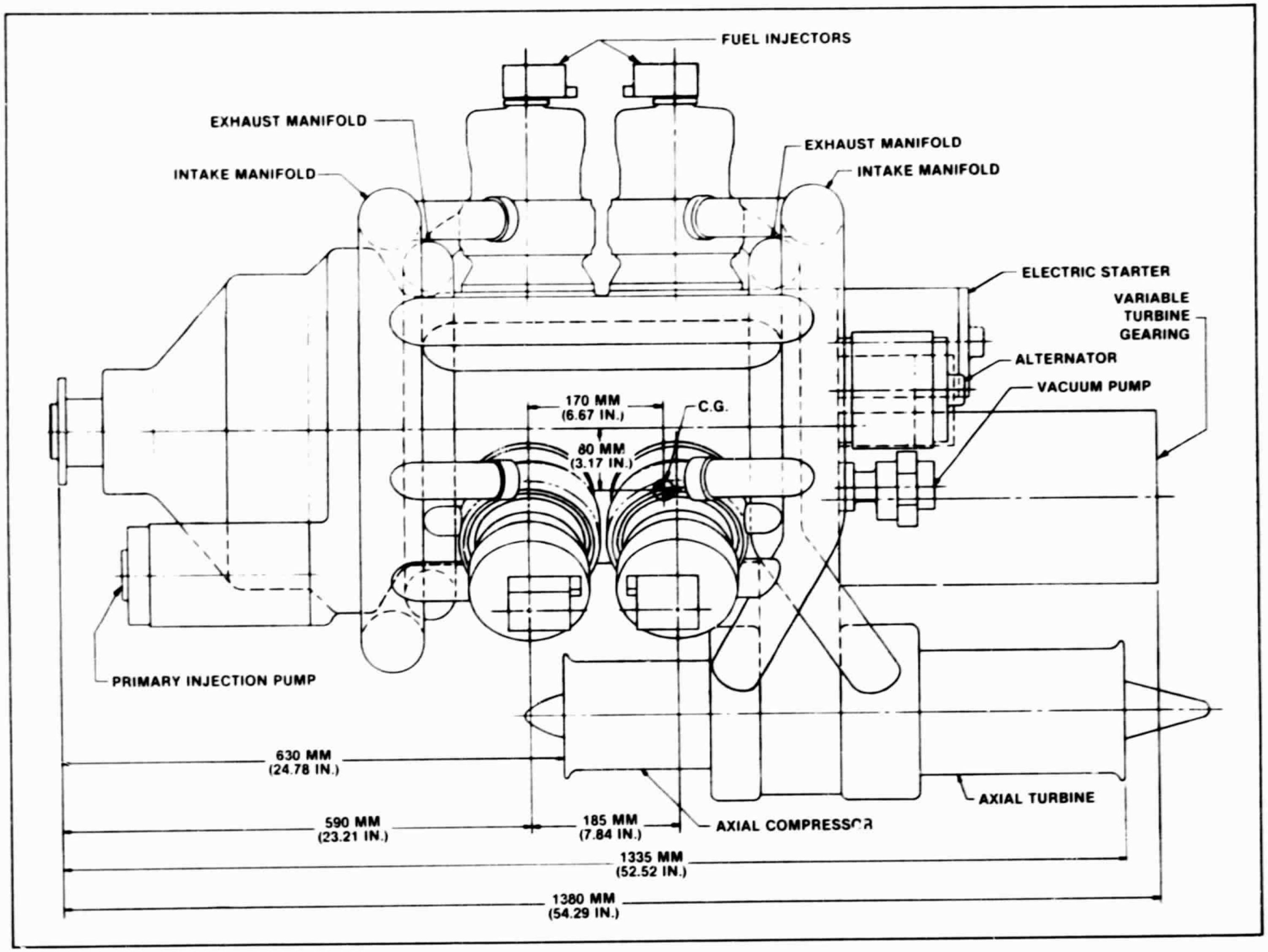


FIGURE 4-3 — 895 kW COMMUTER AIRCRAFT DIESEL - SIDE VIEW

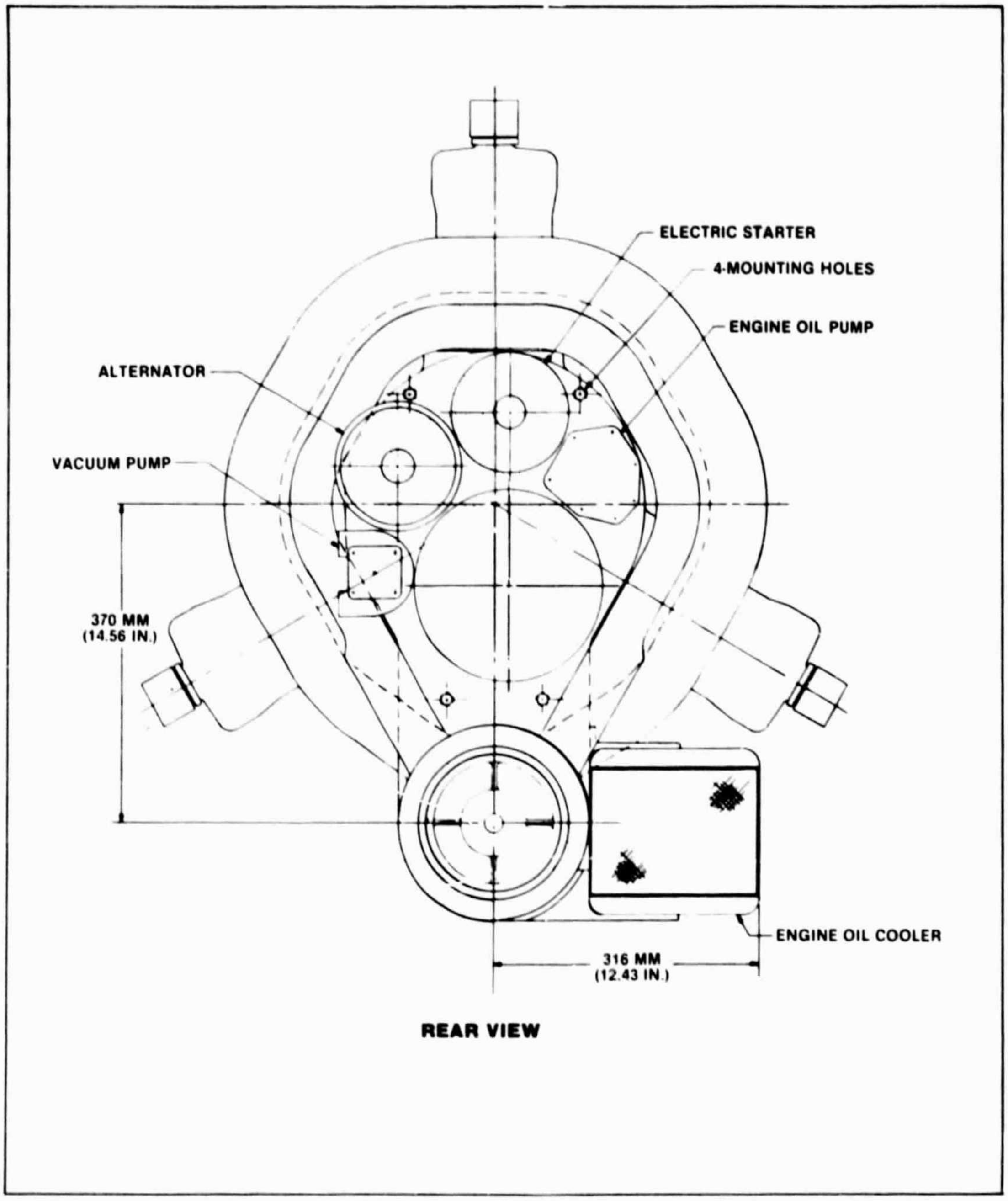


FIGURE 4-4 — 895 kW COMMUTER AIRCRAFT DIESEL - REAR VIEW

4.2 Engine Characteristics

The basic engine characteristics are:

Number of Cylinders	6
Cycle	2 s.c.
Configuration	Radial/Compounded
Bore x Stroke	114 x 124 mm 4.49 x 4.88 in.
Displacement	7.594 l 463.36 cu. in.
Engine Speed	4000 RPM
Piston Speed	16.5 m/s 3255 fpm
Piston Engine Power @ Takeoff	809 kW 1085 HP
BMEP @ Takeoff	15.98 bar 232 psi
Specific Power	106.5 kW/l 2.34 HP/in^3
Propeller Speed	1615 RPM

4.3 Power Schematics

Figures 4-5 through 4-9 show the compounded power schematics for five flight conditions:

- Takeoff
- 100% cruise power at 4572m (15000 ft.) and 7620m (25000 ft.) altitude.
- 65% cruise power at 4572m and 7620m altitude.

Engine	Compressor	Turbine
809 kW/1085 HP	480 kW/643 HP	594 kW/796 HP

Excess Turbine Power	114 kW/153 HP
Gear Train to Crankshaft	– 4 kW/ – 6 HP
	110 kW/147 HP

Power @ Crankshaft	919 kW/1232 HP
Accessory Power	– 15 kW/ – 20 HP
	904 kW/1212 HP
Prop Gearing Loss	– 9 kW/ – 12 HP
Nominal Prop Power	895 kW/1200 HP

FIGURE 4-5 — POWER SCHEMATIC TAKEOFF MODE

Engine	Compressor	Turbine
753 kW/1010 HP	500 kW/670 HP	688 kW/923 HP

Excess Turbine Power	188 kW/253 HP
Gear Train to Crankshaft	– 4 kW/ – 6 HP
	184 kW/247 HP

Power @ Crankshaft	937 kW/1257 HP
Accessory Power	– 33 kW/ – 45 HP
	904 kW/1212 HP
Prop Gearing Loss	– 9 kW/ – 12 HP
Nominal Prop Power	895 kW/1200 HP

FIGURE 4-6 — POWER SCHEMATIC 100% CRUISE POWER @ 4572m (15000 FT.) ALTITUDE

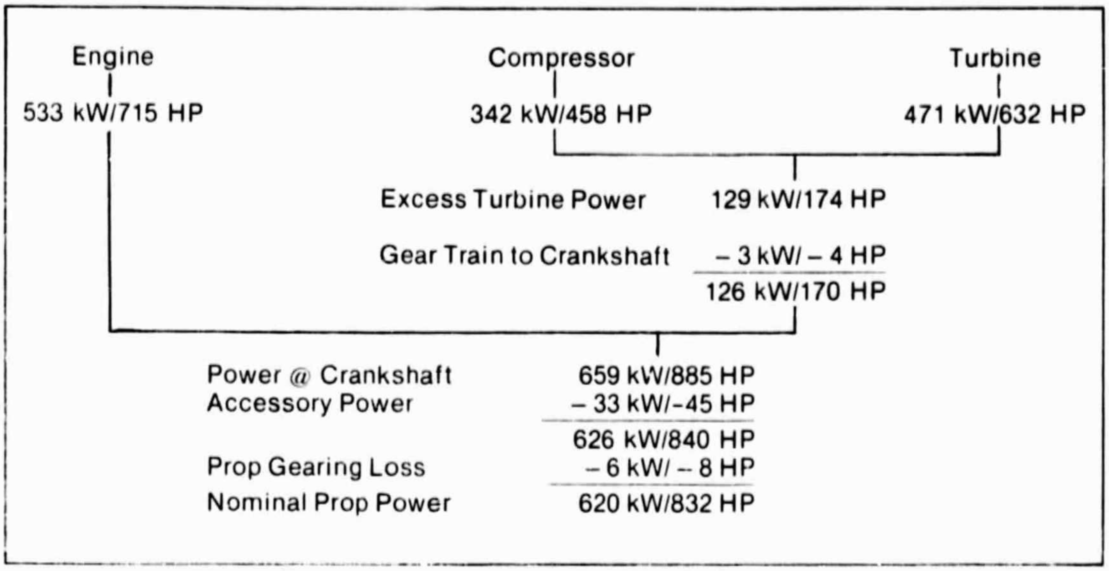


FIGURE 4-7 — POWER SCHEMATIC 100% CRUISE POWER @ 7620m (25000 FT.) ALTITUDE

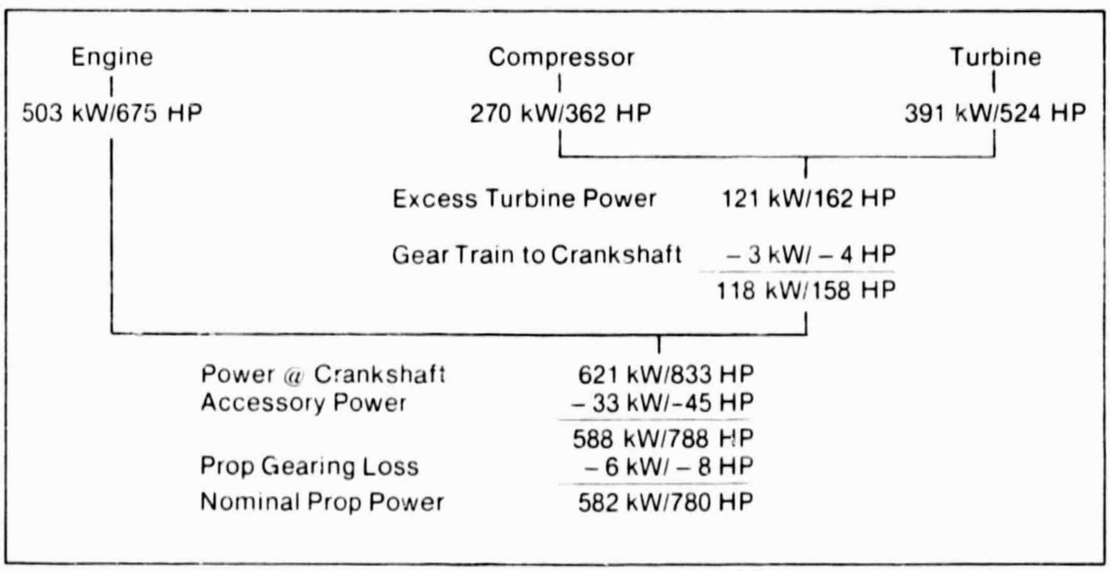


FIGURE 4-8 — POWER SCHEMATIC 65% CRUISE POWER @ 4572m (15000 FT.) ALTITUDE

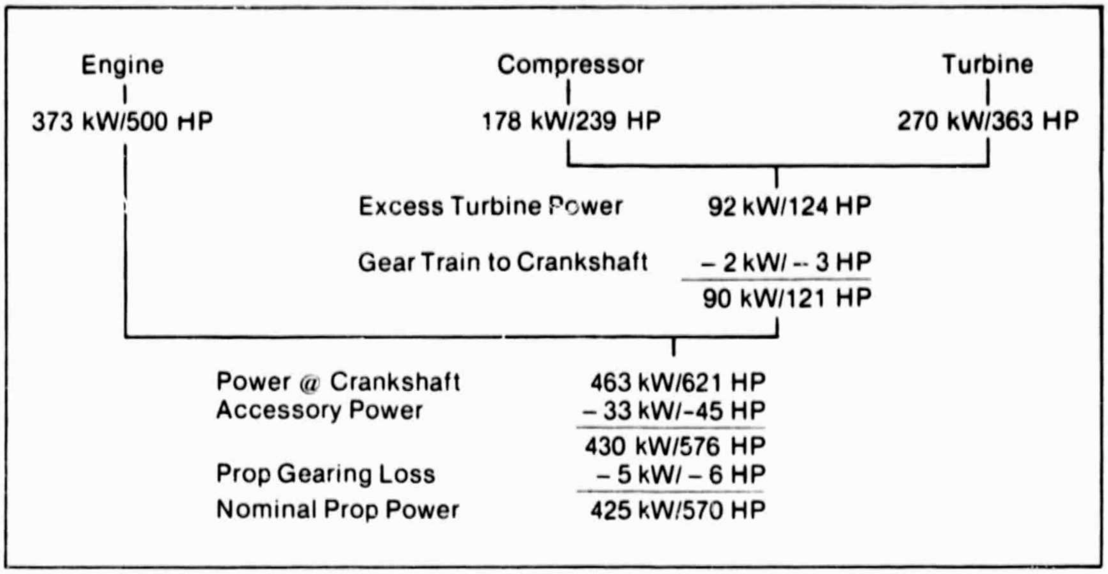


FIGURE 4-9 — POWER SCHEMATIC 65% CRUISE POWER @ 7620m (25000 FT.) ALTITUDE

4.4 Performance Data Up to 7620m (25000 ft.) Altitude

1. Performance summary.

Table XI is a summary of the engine performance parameters.

TABLE XI
Summarized 895 kW Performance Parameters

Altitude	m / ft	Takeoff	100% Power		65% Power	
		Sea Level	4572 / 15000	7620 / 25000	4572 / 15000	7620 / 25000
Assumed Airspeed	km/h		696	691	561	568
	knots		376	373	303	307
	Mach. No.		.60	.62	48	.51
Nominal Prop Power	kW	895	895	620	582	425
	HP	1200	1200	832	780	570
Prop Speed*	RPM	1615	1615	1615	1211	1211
Engine Speed	RPM	4000	4000	4000	3000	3000
Fuel Flow	kg/h	190	167	117	110	79
	lb/h	418	369	257	243	175
Compounded BSFC	g/kWh	212	187	189	189	186
	lb/HPh	.348	.308	.309	.312	.307

*The choice of the propeller speed is based on a propeller tip speed at .8m and a diameter of 3.05m (10 ft.).

2. Propeller shaft horsepower versus engine speed and altitude.

A. Full load prop torque at sea level.

The full load torque and propeller power data shown in Table XII are based on a 5% torque rise characteristic at reduced speed. The maximum torque is at 3000 RPM.

TABLE XII
Full Load Power at Sea Level

Engine RPM	Propeller RPM	Prop Torque N.m	Prop Torque ft-lb	Propeller Power kW	Propeller Power HP
4000	1615	5291	3902	895	1200
3500	1413	5489	4048	812	1089
3000	1211	5556	4097	705	945
2500	1009	5440	4012	575	771

B. Altitude effect.

The engine is flat rated from sea level to 4572m (15000 ft.). The power drops off above that altitude due to the characteristics of the turbine machinery. The maximum obtainable power at 7620m (25000 ft.) is 620 kW (832 HP). Table XIII and Figure 4-10 show the maximum power at sea level and altitude as a function of engine speed.

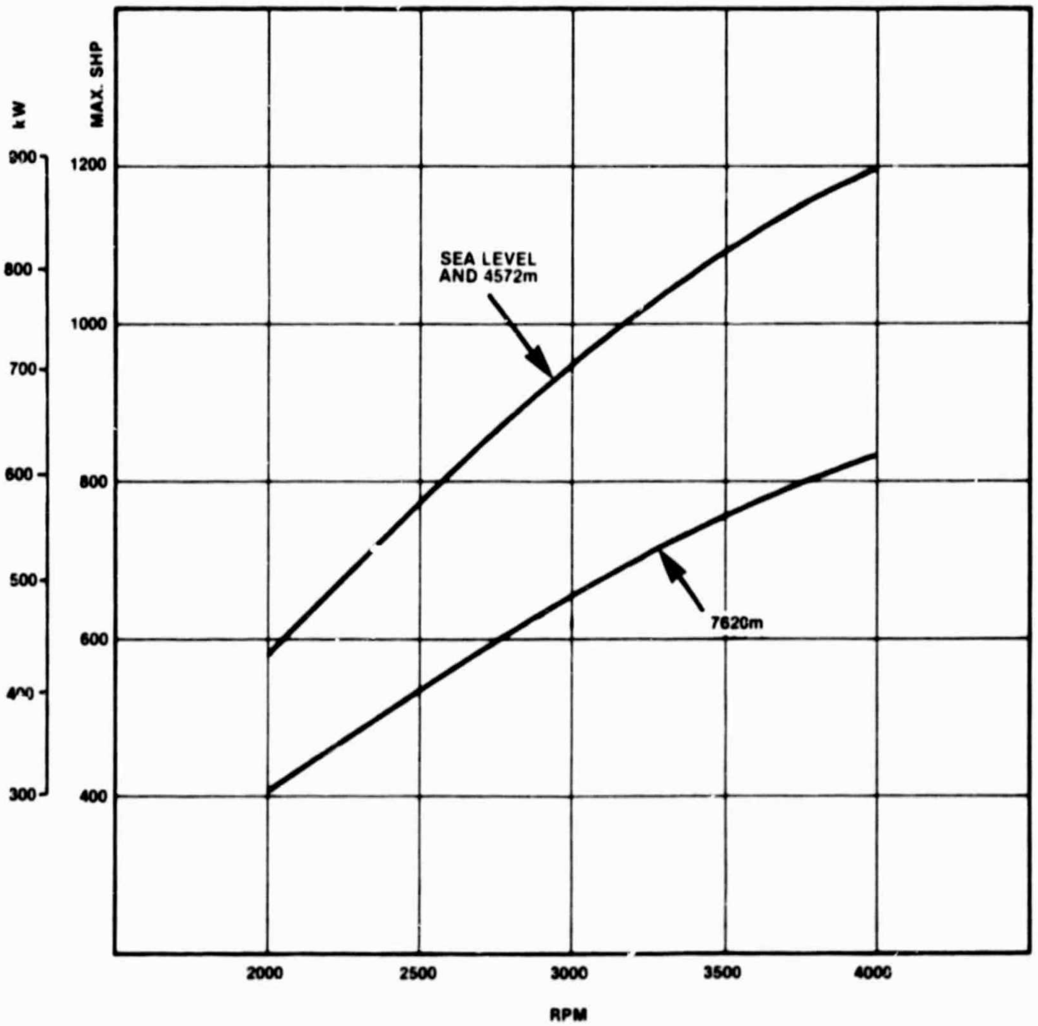


FIGURE 4-10 — 895 kW COMMUTER AIRCRAFT DIESEL MAXIMUM SHP VERSUS RPM

TABLE XIII
Full Load Power at Sea Level and Altitude

RPM		Propeller Power					
Engine	Prop	Sea Level		4572m (15000 ft.)		7620m (25000 ft.)	
		kW	HP	kW	HP	kW	HP
4000	1615	895	1200	895	1200	620	832
3500	1413	812	1089	812	1089	563	755
3000	1211	705	945	705	945	488	655
2500	1009	575	771	575	771	399	535

C. Fuel flow vs. RPM and altitude.

Tables XIV, XV and XVI show the fuel flows at maximum power at various engine speeds for takeoff and cruise power conditions.

Figure 4-6 shows these tables in graphical form.

TABLE XIV
Fuel Flow at Sea Level at Max. SHP

RPM	Prop kW HP	Cranksh. kW HP	Turbine % Total	Turbine Net kW HP	Engine kW HP	Piston Engine BSFC g/kWh lb/HPh	Fuel Flow kg/h lb/h	Compounded BSFC g/kWh lb/HPh
4000	895 1200	919 1232	11.9	110 147	809 1085	234 .385	190 418	212 .348
3500	812 1089	835 1120	8.5	71 95	764 1025	225 .370	172 379	212 .348
3000	705 945	726 947	5.0	37 49	690 925	222 .365	153 338	217 .358
2500	575 771	596 799	0	0 0	596 799	225 .370	134 296	233 .384

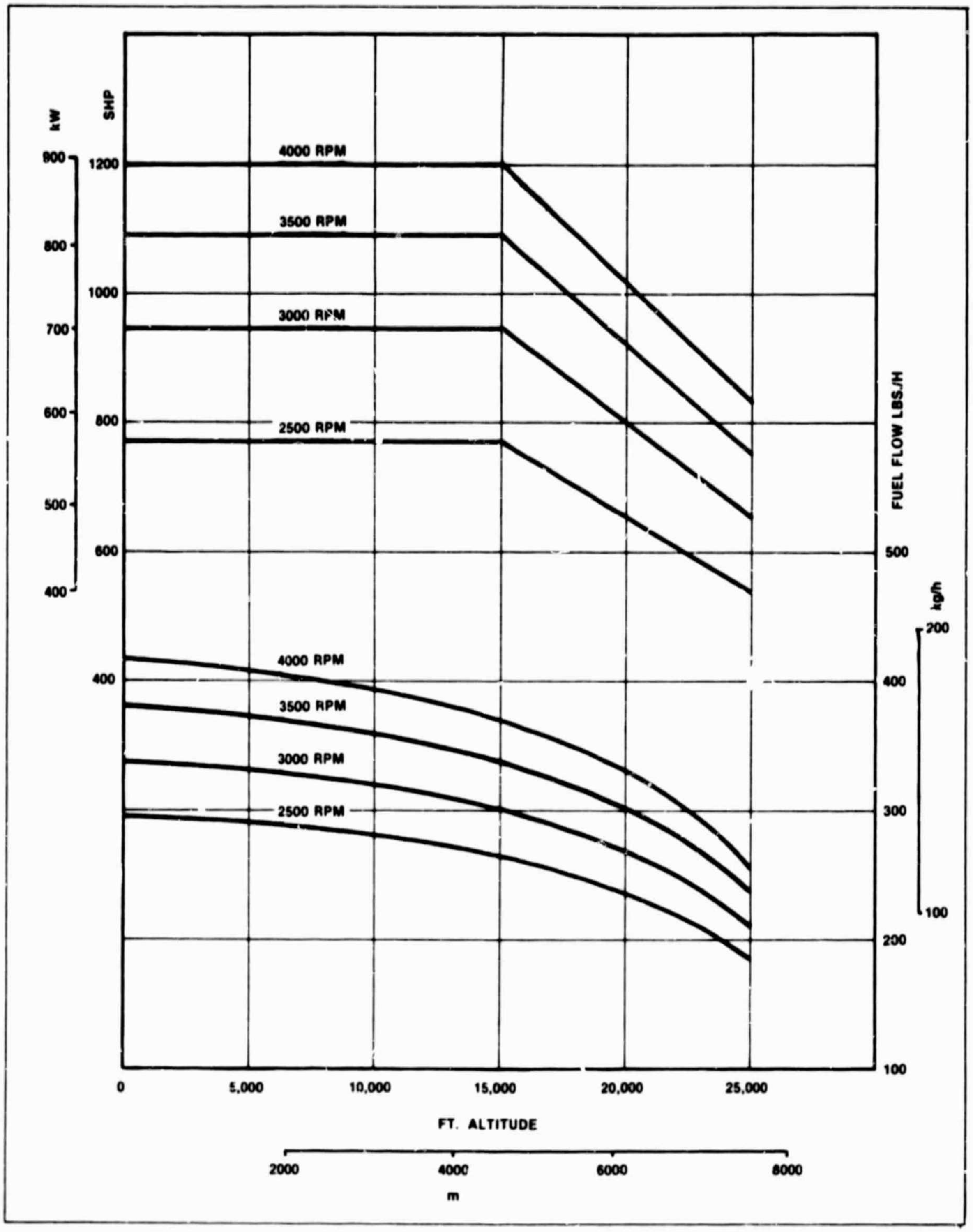


FIGURE 4-11 — 895 kW COMMUTER AIRCRAFT DIESEL MAXIMUM SHP AND FUEL FLOW

TABLE XV
895 kW Fuel Flow at 4572m (15000 ft.) at Max. SHP

RPM	Prop kW HP	Cranksh. kW HP	Turbine % Total	Turbine Net kW HP	Engine kW HP	Piston Engine BSFC g/kWh lb/HPh	Compounded Fuel Flow kg/h lb/h	BSFC g/kWh lb/HPh
4000	895 1200	937 1257	19.6	184 247	753 1010	222 .365	167 369	187 .308
3500	812 1089	854 1145	18.0	154 206	700 939	219 .360	153 338	188 .310
3000	705 945	744 998	16.0	119 160	625 838	219 .360	137 302	194 .320
2500	575 771	614 824	13.0	80 107	535 717	225 .370	120 265	209 .344

TABLE XVI
895 kW Fuel Flow at 7620m (25000 ft.) at Max. SHP

RPM	Prop kW HP	Cranksh. kW HP	Turbine % Total	Turbine Net kW HP	Engine kW HP	Piston Engine BSFC G/kWh lb/HPh	Compounded Fuel Flow kg/h lb/h	BSFC g/kWh lb/HPh
4000	620 832	660 885	19.2	127 170	533 715	219 .360	117 257	189 .309
3500	563 755	602 807	17.5	105 141	497 666	216 .355	107 236	190 .313
3000	488 655	526 706	15.5	81 109	445 597	216 .355	96 212	197 .324
2500	399 535	436 585	12.5	54 73	382 512	222 .365	85 187	213 .350

3. Fuel flow at idle RPM.

The estimated idle fuel flow is listed in the tabulation below. Uncertainties are the FMEP and the friction SFC.

Idle Speed	1000 RPM
FMEP	1.52 bar (22 psi)
Friction Power	19 kW (26 HP)
Friction SFC	487 g/kWh (.80 lb/HPh)
Idle Fuel Flow	9.5 kg/h (21 lb/h)

If 15 kW (20 HP) accessory power is included:

Engine Power	34 kW (46 HP)
BSFC	456 g/kWh (.75 lb/HPh)
Fuel Flow	16 kg/h (35 lb/h)

4. Power settings.

Following are full load and part load power settings.

A. Takeoff power at 32.5°C (90°F).

The previous calculations are based on 15.0°C (59°F) ambient air temperature. The temperature correction factor is 1% power reduction per 5.56°C (10°F).

Temp corrected crankshaft power	891 kW (1195 HP)
Accessory power + gear losses	-24 kW (32 HP)
Nominal prop power	867 kW (1163 HP)

B. Maximum climb power @ ISA conditions:

- The power plant is flat rated at 895 kW (1200 SHP) to 4572m (15000 ft.).
- Above 4572m (15000 ft.) the climb power will decrease with altitude from 895 kW (1200 HP) to 620 kW (832 HP) at 7620m (25000 ft.) due to the specific design of the turbo machinery.

C. Partial power @ ISA conditions:

The Figures 4-7 through 4-9 show the fuel flows as a function of the nominal propeller power, engine RPM and altitude. The end points of the curves represent the 100% power setting.

4.5 Engine Physical Characteristics

A study was made of the engine weight, location of the center of gravity and the overall dimensions.

4.5.1 ENGINE WEIGHT ANALYSIS

A weight analysis was conducted of two versions of the proposed engine:

1. A conventional version uses conventional materials.
2. An advanced version of equal performance uses advanced lightweight material technologies.

A detailed weight analysis is shown in Table XVII.

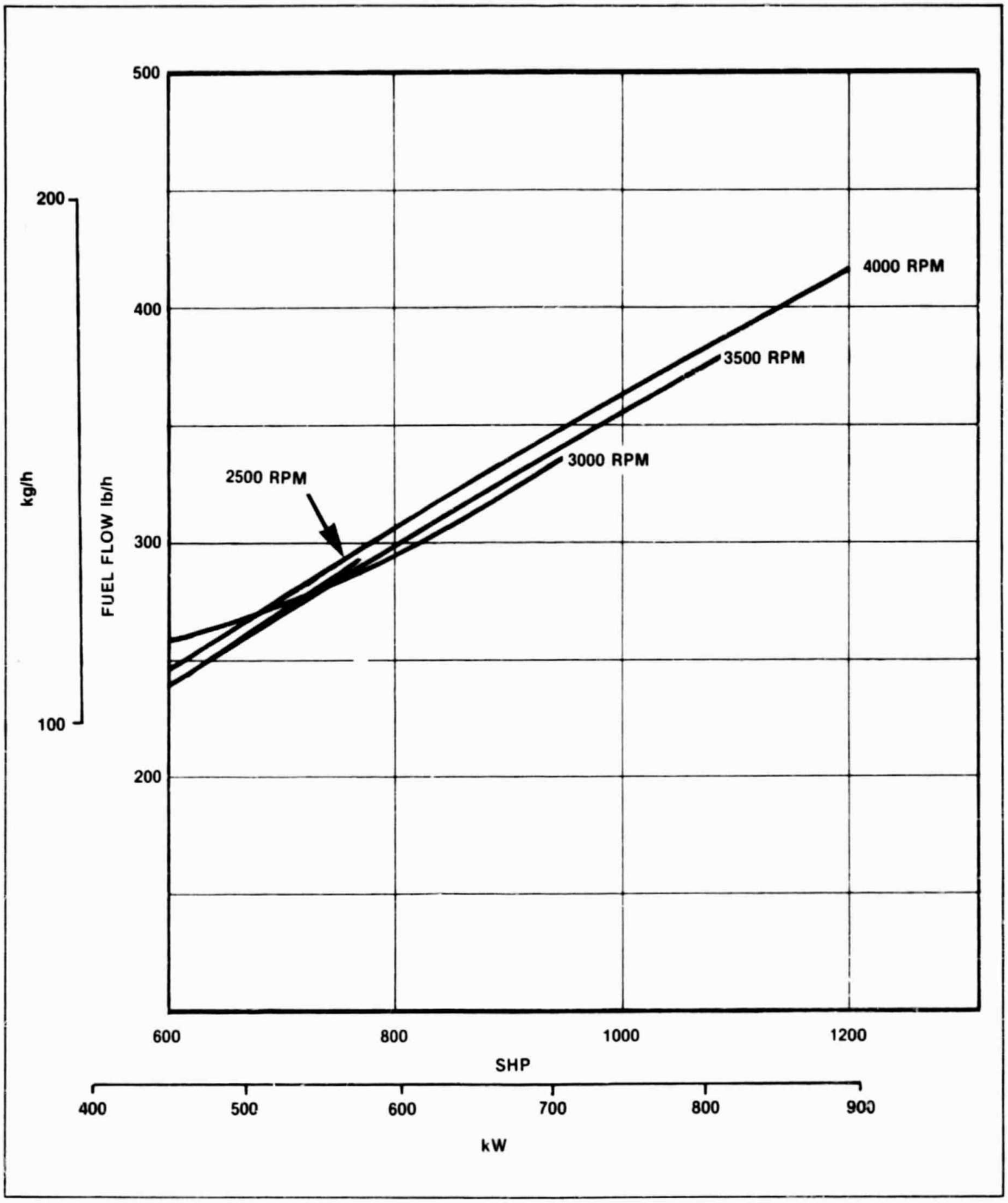


FIGURE 4-12 — 895 kW COMMUTER AIRCRAFT DIESEL PART LOAD FUEL CONSUMPTION AT SEA LEVEL

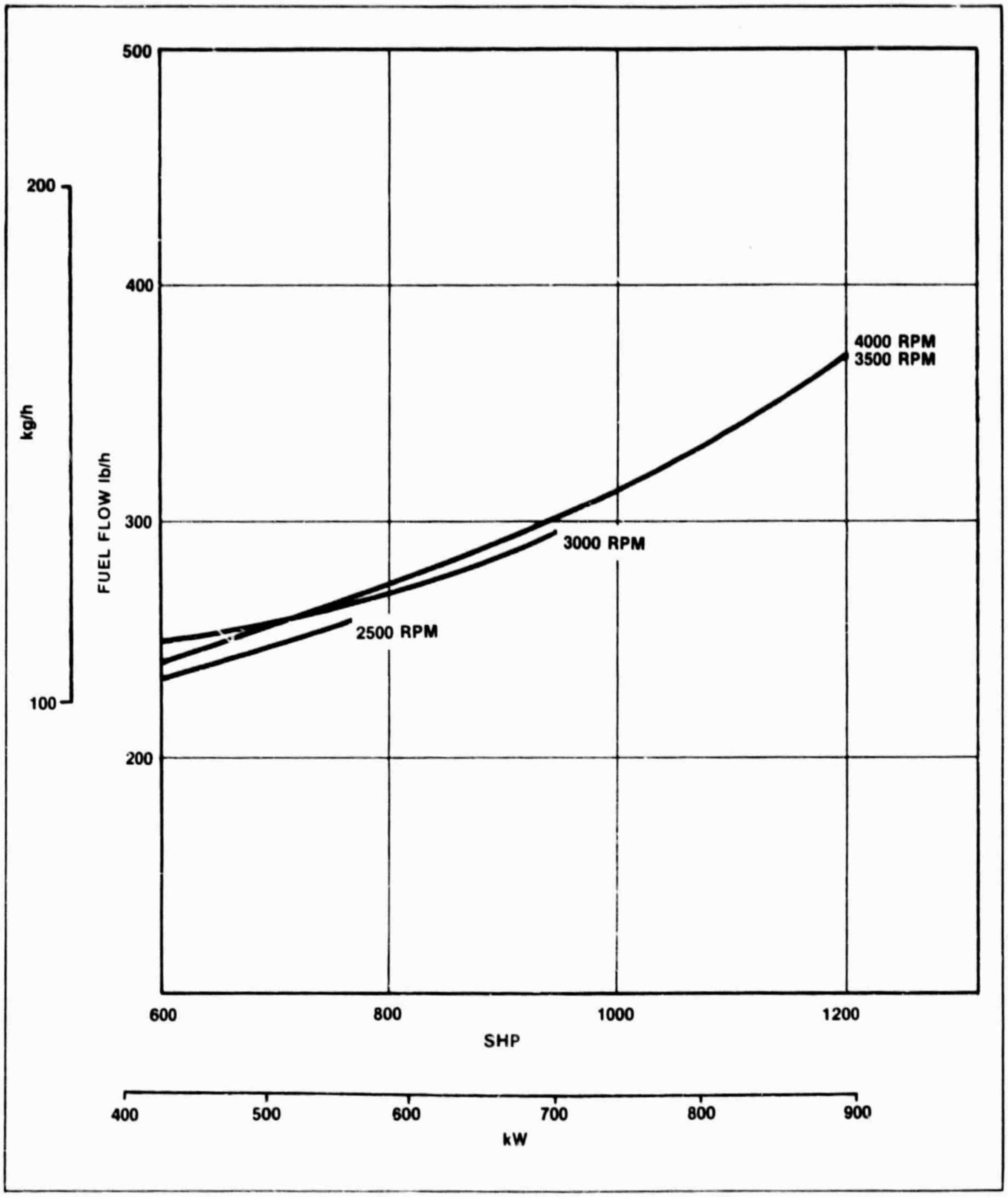


FIGURE 4-13 — 895 kW COMMUTER AIRCRAFT DIESEL PART LOAD FUEL CONSUMPTION AT 4572m ALTITUDE

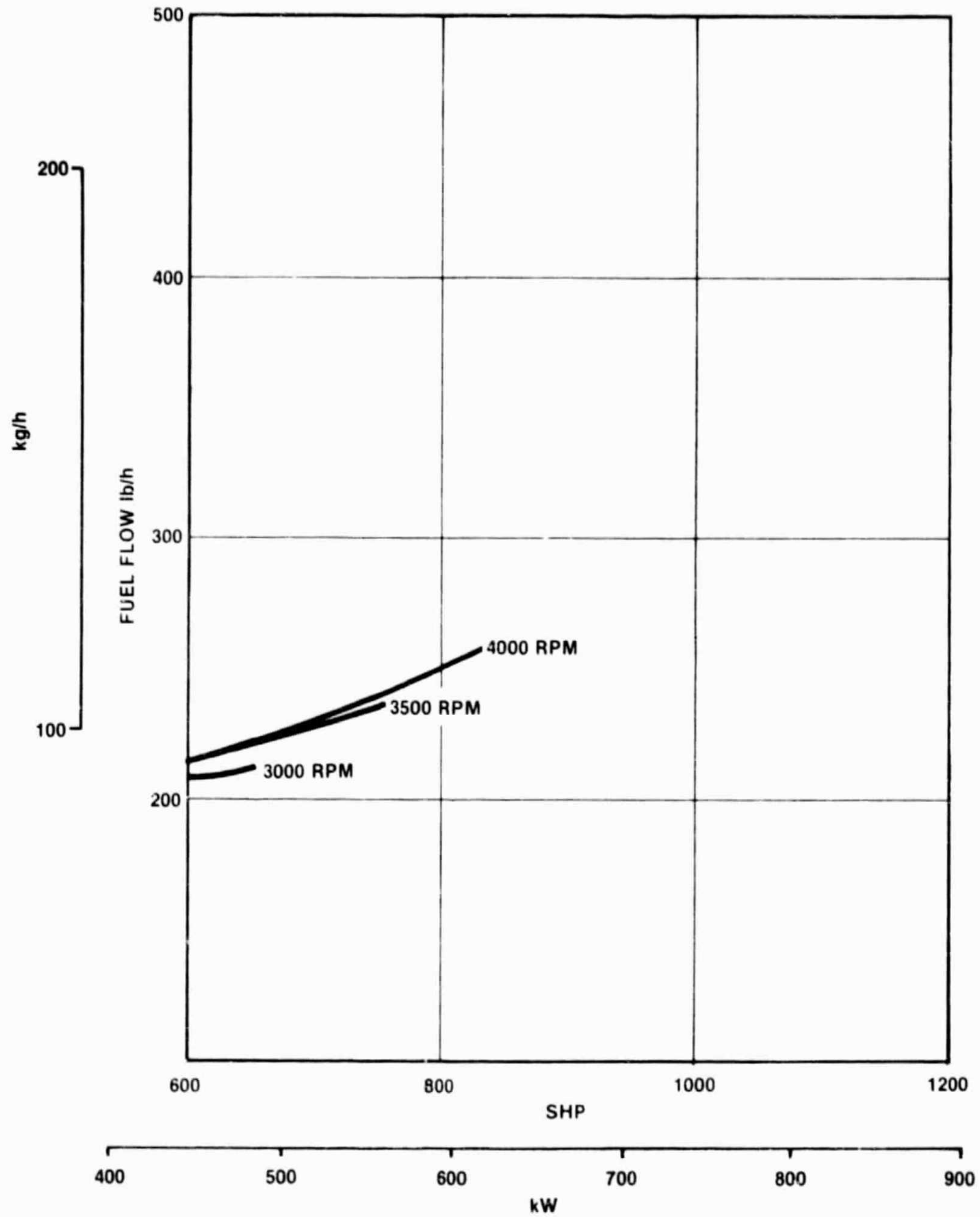


FIGURE 4-14 — 1200 SHP COMMUTER AIRCRAFT DIESEL PART LOAD FUEL CONSUMPTION AT 7620m ALTITUDE

TABLE XVII
895 kW (1200 HP) Weight Analysis

Component	Weight			
	Advanced		Conventional	
	kg	lb	kg	lb
Prop Gear Housing	16	36	19	42
Crankshaft	24	53	24	53
Prop Drive Gear	7	16	8	18
Pinions	15	32	16	36
Sun Gear	3	6	3	6
Cylinders	59	129	59	129
Pistons	21	47	28	62
Piston Pins	6	15	6	15
Connecting Rods	14	31	23	51
Crankcase	13	28	14	34
Intake Manifolds	15	32	18	40
Exhaust Manifolds	14	30	13	30
Accessory Drive Gears	3	7	3	8
Injection System	28	62	28	62
Governor	1	3	1	3
Vacuum Pump	1	3	1	3
Oil Pump	4	9	4	10
Starter	22	48	22	48
Generator	22	48	22	48
Oil Cooler	9	20	9	20
Compressor/Turbine	86	190	110	243
Turbine Drive Gearing	22	48	24	55
Balance of Parts	40	87	45	99
Engine Weight-Dry	445	980	500	1105
Oil & Tank Weight	20	45	20	45
Engine Weight-Wet	465	1025	520	1150

The specific weights, referenced to the 895 kW (1200 SHP) takeoff power are:

	kg/kW	lb/HP
Advanced Materials	.520	.854
Conventional Materials	.581	.958

4.5.2 LOCATION OF THE ENGINE CENTER OF GRAVITY

The center of gravity was determined in two directions. It is assumed to be on the vertical axis of the engine.

A. Horizontally.

170mm (6.67") behind the centerline of the front row of cylinders.

B. Vertically.

80mm (3.34") below the crankshaft centerline.

4.5.3 ENGINE DIMENSIONS

The overall engine dimensions are:

Length	1380mm (54.29 in.)
Width	840mm (33.04 in.)
Height	950mm (37.37 in.)
Volume	1098 dm^3 (38.79 $ft.^3$)
Frontal Area	4394 cm^2 (681 $in.^2$)

5.0 SCALING INFORMATION

The data generated in the Chapters 3 and 4 have been extrapolated to establish the physical characteristics and engine performance data over a power range from 670 kW (900 SHP) to 1865 kW (2500 SHP). All parameters are expressed as a function of the takeoff power at ISA conditions. Because of the specific designs in this study, the equations should not be used to scale data below 900 HP.

5.1 Engine Weight

The weight is defined as the wet weight of a complete power plant and includes all accessories.

1. Advanced Material Engine.

   - Weight $= 10.09\,(\text{kW})^{.564}$ kg where kW = takeoff power in kW

     Specific weight $= 10.09\,(\text{SHP})^{-.436}$ kg/kW

   - Weight $= 18.81\,(\text{SHP})^{.564}$ lb where SHP = takeoff power in HP

     Specific weight $= 18.81\,(\text{SHP})^{-.436}$ lb/HP

2. Conventional Material Engine.

   - Weight $= 8.22\,(\text{kW})^{.610}$ kg

     Specific weight $= 8.22\,(\text{kW})^{-.390}$ kg/kW

   - Weight $= 15.17\,(\text{SHP})^{.610}$ lb

     Specific weight $= 15.17\,(\text{SHP})^{-.390}$ lb/HP

5.2 Size vs. SHP Relationship

No size difference is assumed between advanced and conventional material engines. The difference in cylinder configuration between 6 cylinder and 8 cylinder engines requires a different scaling approach for each arrangement.

1. The following tabulation of cylinder configurations was used to determine the dimensional trends over the considered power range:

SHP		No. of Cylinders	RPM	Displ.		Bore x Stroke	
KW	HP			ℓ	in.^{3}	mm	inch
670	900	6	4400	5.08	310	99.4 x 109.3	3.91 x 4.30
895	1200	6	4000	7.59	463	114.0 x 124.0	4.49 x 4.92
1119	1500	6	4000	9.54	582	122.5 x 134.8	4.82 x 5.31
1119	1500	8	4000	9.54	582	111.3 x 122.5	4.38 x 4.82
1491	2000	8	4000	12.67	773	122.0 x 135.0	4.80 x 5.34
1865	2500	8	3600	17.65	1077	136.7 x 150.3	5.38 x 5.92

2. Width and height of 6 cylinder engines:

SHP kW	Width		Height	
	mm	inch	mm	inch
670	735	28.9	830	32.7
895	839	33.0	949	37.4
1119	905	35.6	1023	40.3

3. Width and height of 8 cylinder engines:

SHP kW	Width		Height	
	mm	inch	mm	inch
1119	679	26.7	813	32.0
1491	751	29.6	900	35.4
1864	833	32.8	998	39.3

4. Engine length of 6 cylinder and 8 cylinder engines:

$L = 498 (kW)^{15}$ mm

$L = 18.75 (SHF)^{15}$ inch.

5.3 Fuel Consumption vs. SHP.

Trends for fuel flow and specific fuel consumption were established for takeoff and maximum cruise power conditions at 4572m (15000 ft.) and 7620m (25000 ft.) altitude.

1. Takeoff power:

- Fuel flow = $.323 (kW)^{938}$ kg/h

  SFC = $.323 (kW)^{-062}$ kg/kWh

- Fuel flow = $.541 (SHP)^{938}$ lb/h

  SFC = $.541 (SHP)^{-062}$ lb/HPh

2. Maximum cruise power at 4572m (15000 ft.) altitude:

- Fuel flow = $.272 (kW)^{945}$ kg/h

  SFC = $.272 (kW)^{-055}$ kg/kWh

- Fuel flow = $.454 (SHP)^{945}$ lb/h

  SFC = $.454 (SHP)^{055}$ lb/HPh

3. Maximum cruise power at 7620m (25000 ft.) altitude:

- Fuel flow = $312 (kW)^{921}$ kg/h

  SFC = $.312 (kW)^{-079}$ kg/kWh

- Fuel flow = $.525 (SHP)^{921}$ lb/h

  SFC = $.525 (SHP)^{-079}$ lb/HPh

6.0 CONCLUSIONS

1. The advanced technology diesel engine with its very low SFC and light weight appears to be an attractive engine candidate for aircraft applications.

2. Diesel engines can have a flat rating potential for full power cruise at higher altitudes which may be advantageous for some applications.

3. Detailed mission studies are required to determine the competitive nature of the diesel engine (relative to other power plants) based on aircraft applications and trip lengths.

4. Additional and more detailed studies are required to obtain engine and maintenance costs.

7.0 LIST OF REFERENCES

1. "150 and 300 kW Lightweight Diesel Aircraft Engine Design Study," NASA Report CR 3260

2. "186 Net kW Lightweight Diesel Aircraft Engine," NASA Report CR 3261

3. "Napier Nomad Aircraft Diesel Engine," H. Sammons and E. Chatterton, SAE Transactions Volume 63, 1955

PRECEDING PAGE BLANK NOT FILMED